# LIFE CYCLE OPTIMIZATION MODEL FOR INTEGRATED COGENERATION AND ENERGY SYSTEMS APPLICATIONS IN BUILDINGS

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# LIFE CYCLE OPTIMIZATION MODEL FOR INTEGRATED COGENERATION AND ENERGY SYSTEMS APPLICATIONS IN BUILDINGS

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Energy use in commercial buildings constitutes a major proportion of the energy consumption and anthropogenic emissions in the USA. Cogeneration systems offer an opportunity to meet a building's electrical and thermal demands from a single energy source. To answer the question of what is the most beneficial and cost effective energy source(s) that can be used to meet the energy demands of the building, optimizations techniques have been implemented in some studies to find the optimum energy system based on reducing cost and maximizing revenues. Due to the significant environmental impacts that can result from meeting the energy demands in buildings, building design should incorporate environmental criteria in the decision making criteria.

The objective of this research is to develop a framework and model to optimize a building's operation by integrating congregation systems and utility systems in order to meet the electrical, heating, and cooling demand by considering the potential life cycle environmental impact that might result from meeting those demands as well as the economical implications. Two LCA Optimization models have been developed within a framework that uses hourly building energy data, life cycle assessment (LCA), and mixed-integer linear programming (MILP). The objective functions that are used in the formulation of the problems include:

- Minimizing life cycle primary energy consumption,
- Minimizing global warming potential,
- Minimizing tropospheric ozone precursor potential,
- Minimizing acidification potential,
- Minimizing $NO_x$, $SO_2$ and $CO_2$, and
- Minimizing life cycle costs, considering a study period of ten years and the lifetime of equipment.

The two LCA optimization models can be used for: (a) long term planning and operational analysis in buildings by analyzing the hourly energy use of a building during a day

and (b) design and quick analysis of building operation based on periodic analysis of energy use of a building in a year. A Pareto-optimal frontier is also derived, which defines the minimum cost required to achieve any level of environmental emission or primary energy usage value or inversely the minimum environmental indicator and primary energy usage value that can be achieved and the cost required to achieve that value.

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# 1.0 INTRODUCTION

## 1.1 ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACTS

Perhaps the most important current issue on the environmental scene is the impact of human activities on climate. Energy related activities attribute to two distinct but interrelated issues that have direct impact on the environment: primary energy consumption and climate change. Primary energy consumption includes both non-renewable resources, such as the consumption of coal, natural gas, petroleum, nuclear electric power, alcohol fuels, wood, waste (secondary energy resource with the potential for re-use), and renewable resources such as the consumption of hydroelectric power, geothermal, solar, and wind. Energy related activities such as exploration, production, and combustion of fuels such as coal, petroleum and natural gas, produce greenhouse gases[1] and aerosols affect the composition of the atmosphere. According to the Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2001), the "*emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate*." Amongst the main conclusions on climate change as summarized in the IPCC report are the following: "*an increasing body of observations gives a collective picture of a warming world and other changes in the climate system; the global average surface temperature has increased over the 20$^{th}$ century by about 0.6°C; snow covers and ice extent have decreased and global average sea level has risen and ocean heat content has increases*."

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[1] Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. Water vapor ($H_2O$), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$), and ozone ($O_3$) are the primary greenhouse gases in the Earth's atmosphere. Human-made greenhouse gases in the atmosphere include halocarbons and other chlorine and bromine containing compounds, hexafluoride ($SF_6$), hydrofluorocarbons (HFCs) and perfluorcarbons (PFCs) (IPCC, 2001).

The definition of climate change in the IPCC report (2001) is as follows:

*Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines "climate change" as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."*

The increase in greenhouse gases and aerosol content in the atmosphere result in a change in the radiative forcing[2] to which the climate system must act to restore the radiative balance. The increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore, an effective radiation into space from a higher altitude at a lower temperature, which causes a radiative forcing, an imbalance that can only be compensated by an increase of the temperature of the surface-troposphere systems, an effect called the "enhanced greenhouse effect" (IPCC, 2001). Although the effect of increasing amount of aerosols on the radiative forcing is complex and not yet well known, the direct effect, although inconsistent because of the short residence time of aerosols in the atmosphere, is the scattering of part of the incoming solar radiation back into space resulting in a negative radiative forcing, which partly and locally offset the enhanced greenhouse effect (IPCC, 2001).

Ozone ($O_3$) is an important greenhouse gas present in both the stratosphere and troposphere. The role of ozone in the atmospheric radiation budget is strongly dependent on the altitude at which changes in ozone concentrations occur. Ozone is not a directly emitted species but rather it is formed in the atmosphere from photochemical processes involving both natural and human-influenced precursor species. Once formed, the residence time of ozone in the atmosphere is relatively short, varying from weeks to months. As a result the estimation of ozone's radiative role is more complex and much less certain than for the long-lived greenhouse gases. The global average radiative forcing due to increases in tropospheric ozone since pre-industrial times is estimated to have enhanced the anthropogenic greenhouse gas forcing. This

[2] Radiative forcing is the change in the net vertical irradiance [expressed in Watts per square meter ($Wm^{-2}$)] at the tropopause due to an internal change or a change in external forcing of the climate system, such as change in the concentration of $CO_2$ or the output of the Sun. Usually radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values (IPCC, 2001).

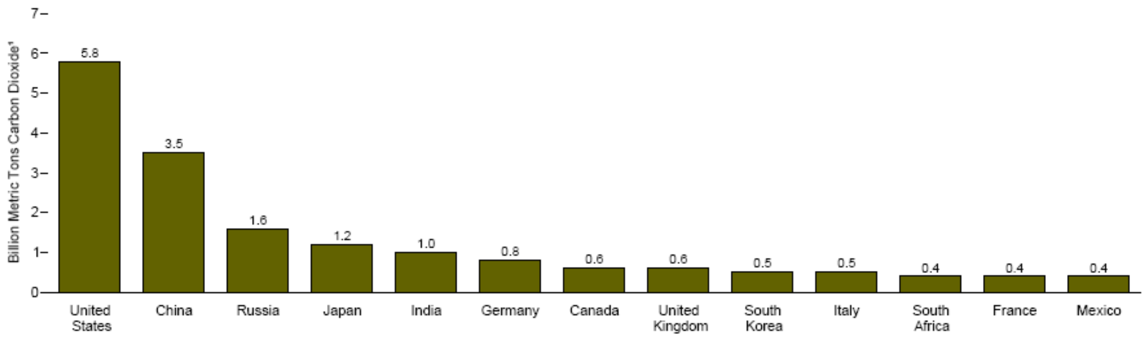


**Figure 1-1: World carbon dioxide emissions in 2003 (EIA (a), 2005).**

makes tropospheric ozone the third most important greenhouse gas after $CO_2$ and $CH_4$ (IPCC, 2001). In addition, surface ozone levels are used as a measure of photochemical ozone formation or smog. Photochemical ozone is responsible for respiratory system distress and eye irritation. Also, photochemical ozone raises particular concern with respect to the wellness of trees and crops.

Other significant reactive gases that have an indirect influence on radiative forcing and also a direct effect on the formation of ozone and acid air emissions are nitrogen oxides ($NO_x$, which is the sum of NO and $NO_2$) and carbon monoxide (CO). The emissions of these gases are directly related to human activities and their concentration are marked especially in industrialized regions. According to IPCC (2001), CO is identified as an important indirect greenhouse gas where the emission of 100 MT of CO is equivalent in terms of greenhouse gas perturbations to the emission of about 5 MT of methane. Carbon monoxide and $NO_x$, as well as sulfur dioxide ($SO_2$, which is another by-product of fuel combustion), are some of the gases that influence the formation of acid air emissions. Acidification represents a local and regional impact affecting the terrestrial ecosystem, the aquatic ecosystem and wildlife. In addition, acid rain damages buildings, construction and sculptures that might have significant value.

The consumption of energy in the form of fossil fuel combustion is the largest single contributor to anthropogenic greenhouse gas emissions in the United States and the world (EIA-b, 2005). In 2003, the USA, which comprises 4.5% of world population, had a 16.8% share of world energy production and 23.4% of the world energy consumption (EIA(a), 2005). Figure 1-1 shows world carbon dioxide emissions, the most significant greenhouse gas, in 2003 resulting

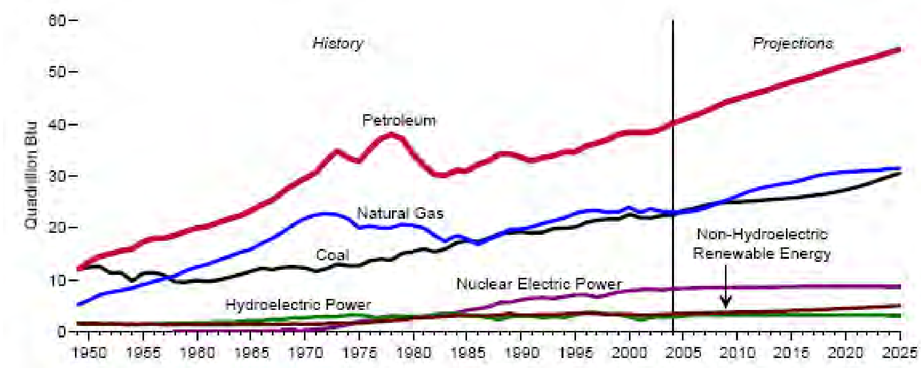


**Figure 1-2: Energy consumption and municipal solid waste combustion (EIA (a), 2005).**

from energy consumption which includes anthropogenic emissions from the consumption of petroleum, natural gas, and coal, and also natural gas venting and flaring; they do not include emissions from geothermal power generation and industrial processes and municipal solid waste combustion (EIA (a), 2005). Figure 1-2 shows energy consumption and its outlook in the USA 1949-2025 (EIA (a), 2005). In the past, most energy consumed in the USA came from fossil fuels; renewable energy resources supplied a relatively small but steady portion, and by the late 1950s, nuclear fuel began to be used to generate electricity, nuclear power surpassing renewable energy in most years since 1988 (EIA(a), 2005). The outlook for the next couple of decades, assuming current laws and policies calls for continued growth and reliance on the three major fossil fuels: petroleum, natural gas, and coal with a modest expansion in renewable resources and relatively flat generation from nuclear electric power.

In 2004, residential and commercial energy consumption accounted for 21% and 18%, respectively, of the total USA primary energy consumption with equal shares of energy related carbon dioxide emissions (EIA(b), 2005). Carbon dioxide emissions represent 84% of the total USA greenhouse gas emissions, mostly resulting from fossil fuel combustion (EIA (b), 2005). Thus, carbon dioxide emissions from the residential and commercial sectors account for 38% of the nation's total energy related carbon dioxide emissions. Figure 1-3 shows carbon dioxide emissions in the USA from different sectors; although the commercial sector generated the lowest carbon dioxide emissions, it recorded the greatest growth since the 1980s (EIA (a), 2005). In the 1990s, electricity sold to residences and commercial sites exceeded sales to industrial sectors. Figure 1-4 gives a breakdown of energy consumption in the residential and commercial

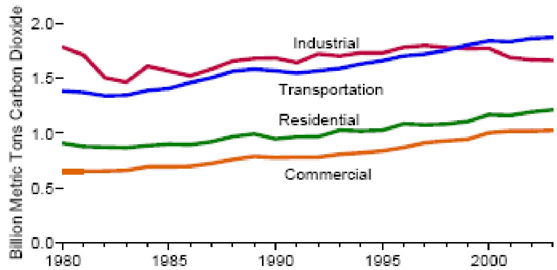


**Figure 1-3: Carbon dioxide in the USA from different sectors (EIA (a), 2005).**


**Figure 1-4: Energy consumption in different sectors in the USA (EIA (a), 2005).**

sectors, and also shown is the energy lost during generation, transmission, and distribution of electricity. Since the origin of emissions in the residential and commercial sectors is predominantly due to electricity-related activities, about 67% in the residential and 78% in the commercial sector (EIA (b), 2005)-improving energy generation efficiencies, optimizing the operation of buildings, and exploring different technology options in energy generation may lead to a reduction in energy use and emissions.

## 1.2 TECHNOLOGIES IN BUILDING'S OPERATION

The average commercial building in the USA requires electrical energy for lighting, office equipment, ventilation, and other mechanical and safety equipment; and thermal energy for space and domestic water heating and cooling. In conventional practice, electrical power is supplied by a utility and is centrally generated and distributed through the power grid to buildings.

Thermal energy is typically supplied on-site by natural gas-fired boilers while cooling is typically supplied by electric chillers. Onsite combined heat and power (CHP) systems, also referred to as cogeneration systems, offer an opportunity to simultaneously meet the building's thermal and electric demand using a single energy source. In addition, the cogenerated heat can be utilized to meet part or all of the cooling demand by using heat-driven absorption chillers. The improvement in energy efficiency may lead to conservation of resources, reduction in emissions and, therefore, overall environmental impact.

According to the USA combined heat and power association (U.S.CHP, 2001), currently there is approximately 56,000 MW of CHP electric generation, which represents 7% of the USA electricity generation capacity in operation. Although CHP has been widely in use in industrial applications, smaller systems have been in use in recent years in commercial buildings and institutions. The CHP industries, USA Department of Energy (DOE), and USA Environmental Protection Agency (EPA) have agreed to double USA CHP capacity between 1999 and 2010. By the year 2010, the goal is to add 8 GW of new capacity in buildings, 8 GW of new district energy CHP, and 5 GW of capacity in federal facilities, in addition to 27 GW of new capacity in industry (U.S. CHPA, 2001).

Figure 1-5 shows an example of conventional heat and electricity supply compared to a cogeneration system, which is a microturbine cogeneration system in this case. In typical practice, 139 kW of natural gas fuel input is required to deliver 111 kW of heat using a gas boiler with 80% thermal efficiency based on fuel input. Also, typically to produce 60 kW of electricity, 188 kW of fuel is required (128 kW of energy is lost) because the electric efficiency of the average electric generation in the USA is 32% based on fuel input, largely because of loss during generation, distribution and transmission of electricity. Thus, the total efficiency of a typical system is 52% of fuel input (327 kW) considering the useful energy output (171 kW). On the other hand, a microturbine cogeneration system requires only 214 kW of fuel input to produce 60 kW of electricity and 111 kW of heat with only 43 kW of wasted energy. The electric efficiency of the microturbine is 28% of fuel input and the thermal efficiency is 52% of fuel input, resulting in 80% total efficiency.

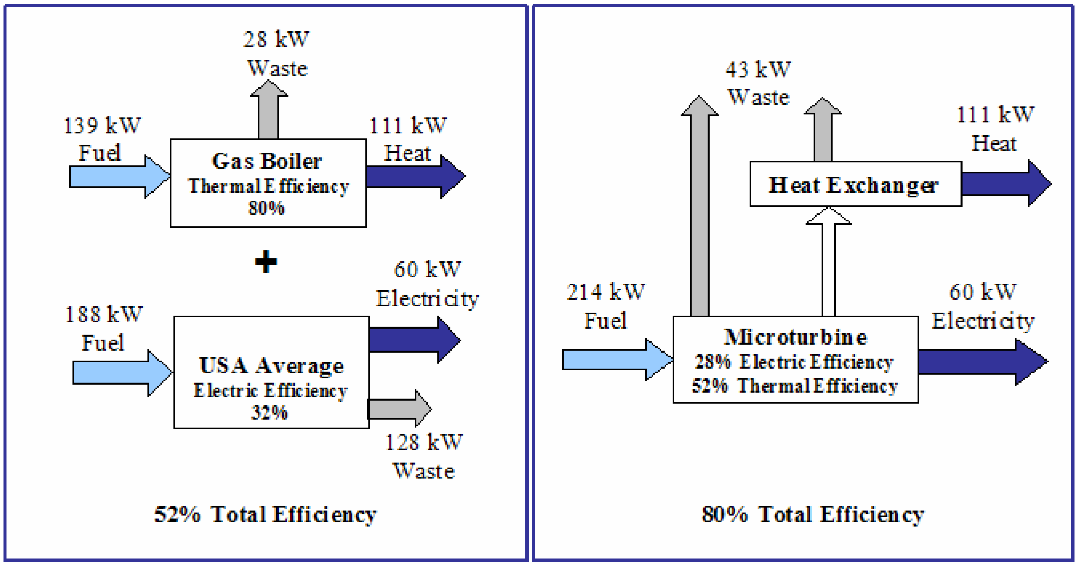


**Figure 1-5: Conventional power and heating supply versus a cogeneration system.**

There are two thermodynamic cycles used in producing energy from cogeneration systems: bottoming cycles and topping cycles. In the bottoming cycle, thermal energy is produced directly from the combustion of fuel; the energy usually takes the form of steam that supplies process heating loads. Waste heat from the process is recovered and used as an energy source to produce electric or mechanical power (Thumann and Mehta, 2001). Whereas in the topping cycle, electricity or mechanical power is produced first; then heat is recovered to meet the thermal loads of the facility.

In order to determine if a cogeneration system is technically and economically feasible, several parameters must be investigated to evaluate the selection, sizing, and operational strategies of a cogeneration system. Cogeneration systems can be operated in various ways depending on the type of energy demand and energy use in a building. The two main parameters that are investigated to evaluate the feasibility of using cogeneration systems are (a) analysis of a building electrical and thermal energy use, and (b) electrical and thermal efficiency ratios of a cogeneration system. The analyses of these data are critical in the selection of the appropriate cogeneration system, equipment sizing, and operational strategies.

Figure 1-6 shows a diagram illustrating the various operational strategies of a cogeneration system as compared to a usual practice or *base case* where electricity is supplied by the electric grid and heat is supplied by a gas boiler. A cogeneration system consists of an electric generator and a heat recovery system, where it can be operated to follow the thermal load

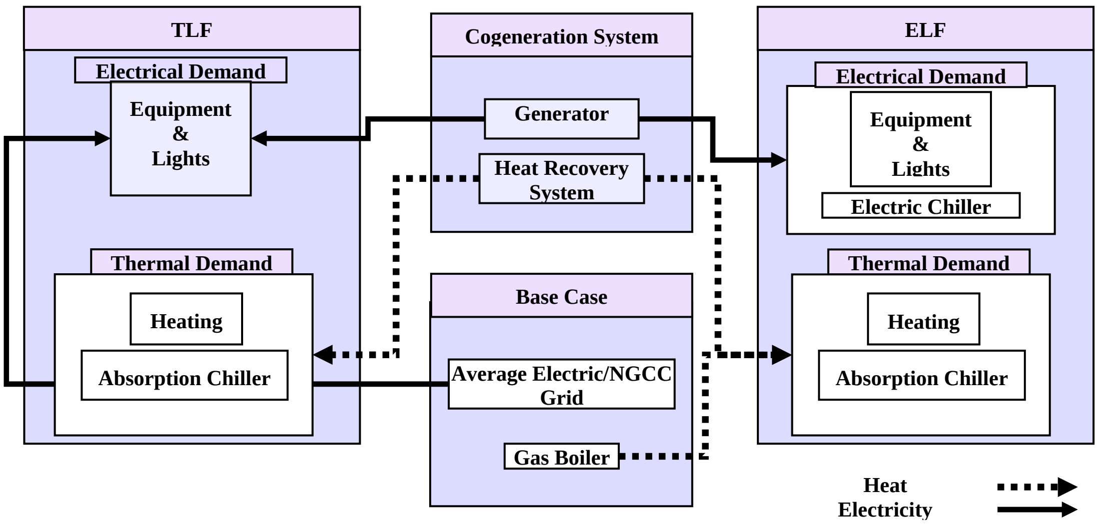


**Figure 1-6: Operation strategies for a cogeneration system.**

following (TLF) or electrical load following mode (ELF). In the TLF strategy, the cogeneration system is operated to meet the thermal load of the building, which consists of space heating and cooling (using heat driven absorption chiller); the cogenerated electricity is used to meet part or the entire electric load required for equipment and lighting and any unmet electric load can be obtained from the grid. In the ELF strategy, the cogeneration system is operated to meet the electric load of the building, which consist of equipment, and lighting as well as cooling (using electric chillers); cogenerated heat is used to meet part or the entire heating load and any unmet thermal load can be obtained from the gas boiler. Also, a cogeneration system can be operated using a hybrid strategy where a system can be periodically adjusted to either TLF or ELF depending on the user’s objective.

Operations research techniques are usually applied to optimize the operation and predict the performance of utility plants. Cogeneration models that have been previously developed in the literature are available in three main areas: simple design-point models, which have been applied for quickly predicting plant performance and providing data for preliminary economic analysis; models that investigate part-load performance of equipment; and optimization models that use operations research techniques to optimize the operation of utility plants to minimize operating cost or to maximize revenue (O'Brien and Bansal, 2000). Despite the range of modeling options available in the literature that were developed to investigate the effects of process parameters on the efficiency of cogeneration systems and the cost of generating electricity, few studies addressed the issue of environmental impacts that could result from building operation. Therefore, operations research is an effective tool that can be used to predict the performance of cogeneration systems and optimize the operation of buildings by considering environmental criteria.

Current cogeneration technologies include: gas turbines, steam turbines, microturbines, internal combustion engines or reciprocation engines, and fuel cells. This research will focus on natural gas driven cogeneration systems of sizes less than 1-MW as they are suitable for commercial building applications. The cogeneration systems that are investigated in this research include: (a) a spark ignited *internal combustion engine* (ICE), which represents a widespread and mature technology for CHP or cogeneration; (b) a *microturbine* (MT), which is an evolving technology in the early stages of application in commercial buildings; and (c) a *solid oxide fuel cell* (SOFC), which represents a new technology that is in development and testing stage, which, because of its modular design, can be used in commercial building applications.

To consider the potential environmental impacts that might result from meeting the energy demand of a building by using a certain technology, it is important to assess the potential impacts throughout an energy system's life. Life cycle assessment (LCA) provides a tool to study the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal (ANSI/ISO, 1997). Considering all of the aspects associated with the materials and fuels used in the production of energy, such as exploration, processing, transportation, transmission, distribution and use, we will provide a framework for understanding and comparing energy systems that are used for electrical and thermal generation and their environmental impacts. By understanding the environmental impact associated with the origins and fate of pollutants resulting from energy generation and use, it would be feasible to minimize the impacts by mitigating the problems at their source.

The environmental impacts resulting from energy use in buildings could be global such as greenhouse gases, or regional, such as acid rain, or local, such as smog formation. In addition, the depletion of natural resources that can result from non-renewable energy consumption is another major environmental impact that can affect the welfare of society and economic growth. Therefore, with the necessity of sustainable use of natural resources and the importance of reducing environmental impacts, building operations should be designed considering not only optimizing energy use to reduce costs but also to implement technologies that can result in lower environmental impacts.

## 1.3 STATEMENT OF RESEARCH

The objective of this research is to develop a framework and model to optimize a building's operation by integrating cogeneration systems and utility systems in order to meet the electrical, heating, and cooling demand. Two life cycle assessment (LCA) optimization models have been developed within a framework that uses hourly building energy data, LCA, and mixed-integer linear programming (MILP). The optimization models are developed by considering the potential life cycle environmental impact that might result from meeting a building's energy demands as well as the economical implications. The objective functions that are used in the formulation of the problems include:

- Minimizing life cycle primary energy consumption (PE),
- Minimizing global warming potential (GWP),
- Minimizing tropospheric ozone precursor potential (TOPP),
- Minimizing acidification potential (AP),
- Minimizing $NO_x$, $SO_2$ and $CO_2$, and
- Minimizing life cycle costs, considering a study period of ten years and the life time of equipment.

A Pareto-optimal frontier is derived, which defines the minimum cost required to achieve any level of environmental emission or primary energy usage value or conversely the minimum environmental indicator and primary energy usage value that can be achieved and the cost required to achieve that value.

The energy systems that are considered as decision variables in the model formulation for electrical, heating, and cooling energy supply include:

- Cogeneration systems: including a solid oxide fuel cell (SOFC), single or multiple microturbines (MT), and single or multiple internal combustion engines (ICE), which could be used to supply electrical and/or thermal energy demands;
- Utility power alternatives: including the USA conventional average electric grid, where electricity consist of a mix of power plants (coal, natural gas, nuclear etc.), and a natural gas-fired combined cycle power plant (NGCC), which is a relatively efficient central power plant;
- Gas-fired boilers, which represent conventional heating in buildings; and
- Electric and absorption chillers, which are used as two options for meeting the cooling requirements in buildings.

An LCA methodology is used in the development of the optimization model. LCA is used for the compilation and evaluation of inputs and outputs to evaluate the potential environmental impacts of a product system throughout its life. The LCA model is developed following the International Organization for Standardization (ISO) framework (ANSI/ISO, 1997). LCA simulation software, GEMIS (Fritsche and Scmidt, 2003), is used to define the energy system characteristics throughout their life cycle and obtain the potential life cycle emission factors and primary energy usage factors resulting from using these systems. The emission results are used as coefficients for the decision variables in the optimization problems. For example, an LCA model for the SOFC cogeneration system includes all of the inputs associated with the manufacturing of the SOFC unit, including all material and fuel production and use in the different stages of the unit's life cycle, as well as the outputs associated with the SOFC unit resulting from the different stage's of the unit's life cycle, such as air emissions associated with the manufacturing of the unit and its use. Therefore, the resultant life cycle emission factor and energy usage factor resulting from the operation of the SOFC cogeneration system to produce a unit energy of output will encompass the cumulative emissions and energy usage factors throughout the SOFC cogeneration system life cycle and not only from emissions from the use phase of the cogeneration system.

The optimization model is developed to allow for integrating different cogeneration systems with utility power plants, gas-boilers and cooling systems (electric and absorption chillers). In addition, the model is formulated to consider the operation of cogeneration systems at different part loads. Electricity can be provided by one or more electric generation source at a specific time of the day, for example, electricity can be provided by a utility source, a MT, a SOFC and/or an ICE. Similarly, heat can be provided by one or more heating sources at a specific time, such as cogeneration systems and/or a gas boiler. Cooling can be provided by an absorption chiller, driven by heat obtained from a gas boiler or a cogeneration process, and/or an electric chiller, driven by electricity from a utility source or a cogeneration process, at a specific time.

Mixed integer linear programming (MILP) is used to develop the optimization model by considering continuous and binary variables in the model formulation. Continuous decision variables are used to determine the energy (electrical, thermal and cooling) supplied from a particular source and binary variables (0-1 variables) are used to determine if a particular cogeneration unit is used at a certain time or not. For instance, if a particular cogeneration unit, e.g. a microturbine, operating at a certain percent load, e.g. 50%, is selected at a certain time, the same unit operating at a different part load can not be selected at that time.

The energy demand consisting of electrical, thermal and cooling loads are known inputs and the values are defined in the model as *parameters*. Energy demand based on hourly loads can be obtained from real time energy use data or it can be simulated using energy simulation tools. Also, the performance characteristics inputs, i.e. efficiencies, capacities and emission factors, of the energy systems are defined as *parameters*. Linear equations are used to describe the correlations between the capacities and efficiencies of energy systems due to the rated and part load status. The relationships between energy demand and energy supply are formulated as linear equations based on the first law of thermodynamics. These equations are considered as constraints in the optimization model. The objective function of the optimization model is formulated by using the continuous decision variables for energy supply and the emission factors are the coefficients of the decision variable for the energy systems.

Two LCA optimization models are developed: an *Hourly LCA Optimization Model* that can be used for long term planning and operational analysis in buildings, and a *Simplified Yearly LCA Optimization Model* that can be used for design and quick analysis of building operation. In addition to evaluating the potential environmental indicators and cost values (i.e. the objective function value), the solution results in determining the optimal values for the decision variables expressing the quantity of electrical, thermal, and cooling energy provided by each system at a particular hour, i.e. the optimum operational strategy.

A hypothetical commercial office building is used as a case study for the LCA optimization model implementation. Energy simulation was used to define the office building characteristics and to generate its hourly energy use data. The two LCA optimization models developed are implemented in the case study to optimize the energy use and investigate the performance of the operation of the building based on the different objectives considered.

The remainder of the dissertation is organized as follows: Chapter (2) includes a literature review on related studies on life cycle assessment and operations research applied in the building's operation design and optimization; Chapter (3) includes background information on the LCA methodology and the LCA models of the energy systems developed as well as the life cycle environmental impact assessment phase including the environmental indicators evaluated for this research; Chapter (4) includes the description of the LCA optimization models developed using MILP and considering the life cycle environmental indicators and economical factors; Chapter (5) includes the description of the hypothetical office building case study, its hourly energy use data, and the implementation of the LCA optimization model on the case study; and Chapter (6) includes the conclusion and contribution section.

# 2.0 LITERATURE REVIEW

## 2.1 LCA STUDIES

The application of LCA methodology in combination with OR techniques to estimate the environmental impacts of meeting the energy demand in buildings has not been extensively documented in the literature. A study was reported in the proceedings of 2000 International Joint Power Generation Conference on using a LCA scheme to estimate the environmental impacts of fuel fired cogeneration plants (Kato *et al.*, 2000). Their proposed scheme used an eco-load standardization scheme (ESS) as a numerical measure for estimating the environmental load of an arbitrarily selected co-generation energy system expressed using a new standardized unit of 'NETS' (Numerical Eco-load Total Standard), which evaluated various kinds of environmental impacts and combined that into a single unit. The ESS scheme involved the following steps: a reference value (the maximum permissible load value for a living thing to survive), was determined; the carrying capacity was assessed depending on the category of environmental impact, the maximum allowable amount of an environmental load was derived, the environmental load per specific functional unit was then obtained; and finally, the overall evaluation of environmental impact was calculated through the life. The proposed scheme for finding the minimum load operation applied the simplex and branch-bound methods to find the optimized solution of objective functions in linear programming. The cogeneration energy system consisted of a gas turbine, waste-heat recovery boilers, auxiliary boilers, steam turbines, electricity driven turbo refrigerators, steam absorption refrigerators and heat exchangers. Although the overall approach provides the user with the simplicity of data configuration using a graphic user interface and the convenience of estimating the environmental impacts resulting from fuel fired-cogeneration using a single unit (NETS), it introduces the complexity and controversial issues of judgments in weighting and normalization of environmental impacts.

Most of the LCA studies were carried out to assess the environmental impact of electric generation from various electric generation processes. A life cycle assessment study was conducted to assess the environmental impacts of four different types of energy systems delivering heat, transportation, electricity, and combined heat and electricity, for continental European energy systems (Michaelis, 1998). For the delivery of heat to domestic consumers, it was found that there was little difference in natural gas and heating oil fuel in terms of greenhouse gas emissions and eutrophication but heating oil systems had higher acidification potential and resource depletion. It was also found that the environmental impacts of the supply of natural gas to the user were small relative to those from its combustion in boilers. For supplying heating oil, although the greenhouse gas emissions were found to be small, the impacts due to extraction, processing and distribution were significant. The supply of electricity considers: oil, coal, natural gas, nuclear, and solar-derived electricity. Of the fossil fuel electricity production systems, natural gas was found to produce the lowest acidification and eutrophication impact, coal was found to produce the largest greenhouse gas emissions, and oil was found to have the largest impact on resource depletion. Photovoltaic electricity was found to have the lowest environmental impact when compared to the other systems except in acidification where it exceeded that of natural gas electricity. Nuclear power had the lowest environmental impact of all systems as its main emissions were radioactive emissions. In addition, it was found that the supply of electricity to consumers using natural gas as a fuel had the lowest impact if a combined heat and power plant was used; however, when natural gas was used to produce electricity, which was transformed to heat and power at the point of use, it had the highest environmental impact when compared to the other systems. The article provided detailed information on the LCA approach used as well as descriptions of the energy producing and delivering systems.

(Spath and Mann, 2000) performed a life cycle assessment to quantify and analyze the environmental aspects of producing electricity from a natural gas combined cycle (NGCC) power generation system, including all necessary upstream operations. A software program was used to model (design and analyze) the NGCC and another software program was used to track the material and energy flows between the process blocks within the system. Two Siemens Westinghouse gas turbines, three pressure heat recovery steam generators, and a condensing steam turbine were used to build the model for the NGCC. For the GWP, $CO_2$ was found to be responsible for 88% and 11.6% of the system GWP and $CH_4$, respectively. Nearly all of the methane emissions resulted from natural gas losses during extraction and distribution while most of the carbon dioxide emissions resulted from the power plant operation. It was found that power plant operating emissions (principally $CO_2$) were responsible for 75% of the system GWP and natural gas production and distribution was responsible for 25%. From sensitivity analyses performed in the LCA, it was found that increasing the power plant efficiency (meaning that more electricity was produced per unit of fossil fuel) and reducing natural gas losses would lower the environmental impact of the system. In addition, a comparison between environmental impacts from using coal versus natural gas in generating electricity was included in the article. Because of the differences in feedstock composition, coal plants were noted for producing more CO, $SO_x$, $NO_x$, and particulates, and also generated a large amount of waste per kWh of electricity produced. In addition, the lower levels of criteria air pollutants resulted in lower capital and operating expenses associated with meeting air quality regulations. Other environmental parameters were included in the article, such as energy and resource consumption, water emissions, and solid waste.

A review of life cycle assessment studies, that were done around the world to evaluate the environmental impacts of electric generation options (hydropower, diesel, natural gas combined cycle turbines, coal, heavy oil, biomass, nuclear, wind, and solar voltaic), showed that coal was found to have the highest greenhouse gas emission factor, with twice the emissions of the natural gas combined cycle (Gagnon *et al.*, 2002). A fuel cell (whose greenhouse gases emissions were mainly from reforming natural gas to hydrogen but virtually nothing from their operation) was found to have higher greenhouse gas emission factors than natural gas turbines but less than coal. For acid precipitation, coal was found to have the highest emissions of $SO_2$ without $SO_2$ scrubbing but lower emissions than a natural gas combined cycle and fuel cell with $SO_2$ scrubbing. Also, coal had the highest $NO_x$ emissions with or without $SO_2$ scrubbing, which was less than that from natural gas combined cycle. It was stated that natural gas can be a significant source of acid precipitation when considering the processing of fuel and $NO_x$ emissions. Other environmental parameters such as land requirements, energy payback ratio, and health issues were discussed in the article. The main findings were that hydropower and wind-power had excellent performance, nuclear energy had excellent performance when radioactive wastes and concerns about catastrophic accidents were not considered (these issues were not included in the

LCA), natural gas generation was found to be better than coal or oil-fired generation, but it had high emissions relative to renewable sources, and coal was found to have the worst performance on most environmental impacts.

A life cycle assessment study was performed to address the use of fuel cells and relevant fuel chains and their environmental impact (Pehnt, 2003). The author used two examples to demonstrate the use of fuel cells and their environmental impacts: SOFC application in industrial cogeneration and centralized electricity production (used natural gas as fuel), and fuel cell application in a passenger car. GWP and acidification were used as examples of environmental impact. For the stationary application of the SOFC, fuel supply, including exploration, extraction, processing, and transport; manufacturing and recycling of the SOFC; operation; and recycling and disposal were considered in the life cycle assessment. For GWP, a SOFC[3] in cogeneration was found to be 12% more efficient than a future gas turbine, and 47% more efficient than a future German electricity generation mix. It was also found that the SOFC produces 70% less acidification than a low $NO_x$ gas turbine and 30% less than a modern natural gas combined cycle. The acidification emissions from the SOFC stemmed from the energy chain and the production of the system while for gas turbines, 50% of total acidification came from direct $NO_x$ emissions. The results also showed that although the global warming potential of the SOFC with CHP was lower than the SOFC only, the global warming potential of the SOFC (CHP), SOFC, gas turbine (CHP), and NGCC were all comparable and were lower than that of average electricity.

Carbon dioxide reduction using technical solutions in three hypothetical plants for power production had been performed in a study (Lombardi, 2003). The three possibilities considered in the project were: natural gas fired combined cycle with partial recirculation of the flue gas and chemical absorption of $CO_2$ from exhausts; an integrated coal gasification combined cycle with $CO_2$ chemical absorption from the syngas; and an innovative methane fueled cycle, where, due to combustion of pure oxygen, $CO_2$ was the cycle working fluid. While in the first two plants, $CO_2$ was removed by chemical absorption, the integrated coal methane fueled cycle had no emission at the stack during the operation phase because $CO_2$ was extracted in almost pure form in the

[3] The results for GWP from the SOFC cogeneration relative to the gas turbine seems contradictory to the conclusion obtained from the LCA study performed by Gagnon *et al.* (2002) as well as the conclusion of our study, where the FC had higher greenhouse gas emission factors compared to the gas turbine.

liquid phase due to high pressure operation. A life cycle assessment was used as comparison criteria for the options studied, considering the entire life time of the plants: construction, operation, and dismantling. The results showed that the methane fueled cycle had no net $CO_2$ emissions, followed by the natural gas-fired combined cycle which had about half the amount of $CO_2$ emissions per MWh as the integrated coal gasification combined cycle. It was also concluded that since most of the emissions were found to result from the operation phase, attention must be focused on this phase since the construction and maintenance phases contributed negligibly to the emissions. It was also stated that the best solution was to develop machinery to operate the methane-fueled cycle but the addition of $CO_2$ chemical absorption can supply great advantage with respect to the present state-of-art in power generation technology. The paper also includes an exergetic life cycle assessment, which had similar conclusions to the LCA study. A detailed description and analysis of the LCA and exergetic LCA of the natural gas fired combined cycle with partial recirculation of the flue gas and chemical absorption of $CO_2$ from exhausts is presented in another study (Lombardi, 2001).

An analysis of a chemical process was performed by implementing a combination of LCA and multi-objective system optimization to identify trade-offs in production, cost, and environmental burdens and impacts (Azapagic and Clift, 1999). The process is simultaneously optimized on a number of environmental objective functions to identify the best compromise solution for improving the system's performance. The advantage of multi-objective optimization in environmental system management in the context of LCA lies in offering a set of alternative options for system improvements rather than a single optimum solution.

## 2.2 STUDIES ON COGENERATION/CHP APPLICATIONS IN COMMERCIAL BUILDINGS

Several studies that are documented in literature were performed to investigate the application of combined heat and power (CHP) technologies in commercial buildings regarding their technical and economical feasibility. A medium-sized office building located in the University of Maryland was used to demonstrate the potential for CHP application in commercial buildings (Marantan *et al.*, 2002). A data-acquisition system and measurement equipment were used to determine the performance of the building in existing conditions and to provide a baseline to be used for performance improvement comparisons. Natural gas was mainly used for water heating and electricity was used for space heating and cooling; both natural gas and electricity were purchased from local utilities. Findings from the study showed that improvements could be made by utilizing desiccant dehumidifiers to provide direct humidity control as part of a building's CHP system; desiccants could be regenerated by using waste heat available from CHP power generating equipment, such as microturbines or fuel cells; and the high electricity consumption during heating and cooling seasons could be reduced by using available heat from power generating equipment for space heating or cooling. This study provides a useful analysis on an existing commercial building operation which sheds light on the energy use profile of the building that can be used in CHP design models and analysis.

Some of the basic and simple models used in predicting the feasibility of CHP applications use a linear relationship between the electric or thermal output of a cogeneration unit and the demand on the site, usually evaluating a single operational strategy at a time, e.g. electrical or thermal load following. Also, another assumption that is usually used in such models is that the electrical and thermal demand is constant, which is not the case in commercial buildings. For example, a simplified model was developed to investigate different optimization techniques for the operation of a cogeneration energy system (Jones, 1999). The techniques studied were thermal tracking (the cogeneration system was operated to meet the hot water demand and supplement the building's electric load), electric tracking (the cogeneration system was used to satisfy the electrical needs of the facility and the supplement the heating load), and economic tracking (calculations were performed to determine the break-even point at which the cost to run the co-generator becomes economically impractical). A microturbine was sized to meet the hot water demand of the athletic building used in the study and both the thermal and economic tracking were found to be the optimal operation strategies. However, although it was economical to always run the co-generator, because of safety issues (no staff to monitor the operation when the facility was closed); it was found that thermal tracking was optimum for the facility.

Another simplified model was developed to evaluate the application of CHP for office buildings (Jalalzadeh-Azar *et al.*, 2002). The study was focused on evaluating the efficiency of microturbine generators on the total primary energy consumption and cost in different climates for a hypothetical office building. In one scenario, the cogeneration units were sized and operated to supply the required heat input of the thermally driven cooling (absorption cooling) and heating systems at any given time; the system relied on power supply from the electric grid because of the limited power generation from the units. In a second scenario, the CHP was sized and operated to meet the electrical energy requirement of the building; when the amount of recoverable heat from the system was insufficient for operating space and water heating systems, gas-fired devices were used to meet the demand, whereas cooling was met by an electric DX system. One of the major findings was that energy consumption and costs for both scenarios were insensitive to the climates considered except for very low electric to gas cost ratios. From the analysis of the result, it was found that the second scenario had a significantly higher yearly energy cost than the first scenario. It was also found that improving the microturbine efficiency had a positive impact on the overall primary energy consumption for both scenarios. It was demonstrated that the implementation of CHP offered opportunities to reduce primary energy consumption and yearly energy cost in addition to providing reliability in supply of electric power. This study provided a simplified linear relation between cogeneration output and demand, which was not accurate for the variable heating and electrical demand of commercial buildings, but this approach was useful for initial evaluation of the application of CHP.

Methods used in distributed generation control in commercial buildings are summarized in an article in the context of the U.S. utility industry (Curtiss, 2000). The methods could integrate building load, generation, and grid information to produce optimal set points for the generator and HVAC system in the building served by a given generation system. Some of the techniques that could be used to control on-site generation are: threshold control, buyback priority, cooling/heating priority control, and optimal control, where distributed generation would be operated using an algorithm that reduces the operating cost over the lifetime of the equipment. Parameters such as building electrical and thermal energy use, water heating, space heating and cooling, as well as electricity and natural gas and utility intensives are all taken into consideration. Several case studies that were investigated in the article showed that the optimal control technique provided an economic benefit over simple threshold control.

The application of fuel cells for CHP in residential and commercial buildings was evaluated in a study which focused mainly in evaluating the economic aspects of using fuel cells (Ellis and Gunes, 2002). The fuel cell CHP system studied included a fuel cell stack, fuel processor (converted hydrocarbons to hydrogen or hydrogen and carbon monoxide), power conditioner (regulated output power), air supply subsystem (provided conditioned air to the fuel cell and fuel processor), thermal management (removed heat from the stack and transferred heat to system components and supplied external thermal loads) and water management subsystems (ensured the removal of water from the stack and that water was available for fuel processing and reactant humidification). The fuel cells discussed in the paper were a proton exchange membrane fuel cell, phosphoric acid fuel cell, molten carbonate fuel cells, and solid oxide fuel cell. The economics of general case studies for fuel cell cogeneration were presented for residential and commercial applications. It was found that CHP systems employing fuel cells could be economically attractive if the initial costs could be reduced to the range of $1000 to $1500/kWe. The article includes detailed description of the fuel cell technologies and general characteristics of fuel cell systems.

A study was performed on the investigation of a fuel cell-based total energy system (TES) for residential application (Gunes, 2001). The size and characteristics of the house studied were based on data available from the Energy Information Administration; the average lighting and domestic hot water use profiles were obtained from the literature; and the space heating and cooling loads were obtained by applying a building energy simulation program. The research was focused on establishing the energy requirements for a single-family residence, modeling the performance of a fuel cell based TES in response to the energy requirements, and evaluating energy use characteristics and life cycle cost for various climatic conditions. The fuel cell system was designed to meet the light and appliance loads as well as space cooling and the thermal output was transferred to a thermal storage tank, which was used for domestic water and space heating. Domestic water and space heating loads that were not met thermally were supplied electrically. A numerical model of the TES was developed and energy savings and economic evaluation (life cycle cost) of the system have been analyzed in the paper. In warmer climates the system was sized for electricity requirements on the peak cooling day and in colder climates the system was sized for the peak heating day. It was found that the TES introduces 32 to 51 percent primary energy savings over conventional residential energy systems. In colder climates, more than 70% of the thermal energy generated in the fuel cell system could be used for heating, which satisfied the thermal and electric load requirements of the building. It was concluded that since the thermal energy was very effectively used by the TES, it was not likely that more complex systems (e.g. absorption cooling) can be justified based on improved utilization of thermal energy.

The use of waste heat from a diesel cycle and gas turbine cogeneration investigated the potential of heat thermoelectric power generators, which convert part of a quantity of heat absorbed directly into electrical power, using an annual cost method based on stack exhaust from a cogeneration system for different operation hours, system life spans, and other cost-related elements including electricity buy back rates (Yodovard *et al.*, 2001). The data used in the analysis was based on different manufacturing industries in Thailand. Gas turbine and diesel cycle cogeneration systems produced electricity estimated at 33% and 40% of fuel input, respectively. The useful waste heat from the stack exhaust (exhaust heat from the heat recovery boiler remaining after the heat was extracted for process steam) of cogeneration systems was estimated at 20% for a gas turbine and 10% for a diesel cycle. The corresponding net power generation was about 100-MWe.

## 2.3 STUDIES ON PERFORMANCE ANALYSIS OF CHP SYSTEMS

Several studies addressed the issue of the effects of process parameters on the efficiency and costs of generating electricity from cogeneration systems, mainly gas turbines and fuel cells. An energetic and economic analysis of solid oxide fuel cells (SOFC) was presented to determine the influence of the variation of cell operation parameters on efficiency and costs of electricity (Riensche *et al.*, 1998 a). It was concluded that the cell voltage and fuel utilization show a cost optimum, and other parameters, such as air temperature increase in the stack and degree of internal reforming, have a uniform influence on efficiency and costs of electricity. The study presented a simplified energetic simulation of the SOFC using a mass flow and energy demand simulation program, a stack modeling program, and FORTRAN, which can be valuable for providing data for design purposes. The influence of plant design on the economy of the SOFC plant was investigated using energetic simulation of the whole plant (Riensche *et al.*, 1998 b). The SOFC plant consisted of the fuel cell stack and the gas processing periphery, and by the analysis of investment and operational costs, the authors concluded that there were two main cost-influencing factors: the demand of preheated air for stack cooling required peripheral units for compression and heat exchange and led to additional energy consumption; and the demand of cell area for optimal electrochemical performance had a strong influence on stack investment costs. Gas recycling by gas blowers or jet boosters was described in the flow-sheets. The findings were that cathode gas recycling by jet boosters turns out to be more advantageous with respect to the costs of electricity than gas recycling by hot gas fans; the influence of pressure drop in the cathode's generator was eliminated and the steam concentration in the exhaust gas was reduced; and the removal of useful heat at higher temperature levels diminished the driving temperature differences and enlarged the heat exchange area of the recuperative heat exchangers located downstream.

A detailed thermodynamic model of a fuel cell was developed using numerical methods that could be used to examine the operation of the fuel cell thermodynamically (Pangalis *et al.*, 2002). Findings from the study showed that the performance of the fuel cell system (SOFC) was strongly affected by the irreversibility developed; for instance, the greater the current flow, the larger the loss in power compared with ideal operation. Other findings showed that although increased operating pressure resulted in higher power output, the additional thermal input to the system for delivering air and fuel at the desired conditions led to a declining trend of efficiency with increasing operating pressure.

The effects of design parameters on the performance of cogeneration cycles was studied where a reversible Carnot cycle was modified for cogeneration with external irreversibility of heat transfer to investigate the effects of the ratios of power to heat demanded by heat consuming processes, extreme temperatures, and heat temperature requirements on the global and optimal performance (Yilmaz, 2004). Findings of the study showed that R (ratio of power output to process heat) = 1 was a critical value for the optimal artificial thermal efficiency. If the process heat was equal to the work output, then the optimal artificial thermal efficiency had a maximum value. On the other hand, R had a negative effect on the energy utilization factor and the exergetic efficiency. Other findings included the effects of extreme temperatures and heat consumer temperature on the optimal performance of a cogeneration system.

## 2.4 STUDIES ON APPLICATIONS OF OPERATIONS RESEARCH TECHNIQUES

Most of the studies that utilize operations research techniques to develop optimization models relating to cogeneration systems are designed to minimize operating costs and/ or minimize energy consumption. Cogeneration models that have been previously developed in the literature are available in three main areas: simple design-point models, which have been applied for quickly predicting plant performance and providing data for preliminary economic analysis; part-load performance models, which have been developed to predict plant performance at part-load conditions; and optimization models that use operations research techniques to optimize the operation of utility plants to minimize operating cost or to maximize revenue (O'Brien and Bansal, 2000).

One of the early models that were used to simulate different operating models was developed using a LOTUS 1-2-3 spreadsheet to test alternative equipment configurations for economic viability, against a background of available equipment cost data, fuel prices, electricity tariffs and their likely uncertainties and tendencies (Fawkes *et al.*, 1998). The model was first developed using empirical data and then the results were applied to a particular site, whose characteristics were believed to be quite typical of public sector flat-dwelling schemes in the United Kingdom. The model incorporated factors necessary to assess the viability of using micro-CHP in a district heating context. Although applying the model with its set of data assumptions to the proposed case showed that micro-CHP could be economically viable with a small margin of benefit relative to existing methods of heat supply (gas-fired boilers), the authors predicted that the results could be more economically viable when used in other applications with a better balance of summer-to-winter heat loadings and size/occupancy factors.

Although the model was useful in sizing CHP plant and calculating the economic variables associated with the CHP plant design, its limitations lay in the assumptions set for predicting the operation of the CHP plant. The assumptions used in the study were; first, when calculating the load factor[4] of the plant, either an electric or thermal demand is used depending on the operating mode being simulated, thus limiting the choice of operation of CHP plant to a single operating mode. Second, the load factor was set not to exceed or go below given limits, a limitation that varies with different engines and operating conditions in practice.

Some of the models that could be used for design analysis and decision making are simple linear and mixed integer linear programming where the objective function is usually formulated to minimize cost or energy consumption subject to linear constraints relating supply and demand and defining system capacities and efficiencies. A model was developed as a mixed integer (0-1) linear programming model to determine the economically optimum energy-mix during short and long term periods and to evaluate the various technologies that can improve the energy supply system (Arivalagan *et al.*, 1995). The model is useful for policy decision making related to energy systems application in industry but lacked the complex modeling of energy systems' performance in part-load conditions and optimization of the operation of these systems during hourly variable loads.

A mixed integer linear programming model was developed to define the optimal configurations of the utility system to be used to satisfy the minimum energy requirements of a given system at minimum costs (Marechal and Kalitventzeff, 1998). The paper includes detailed modeling of the thermodynamics of the process, which is a gas turbine in this case. This model was useful in decision making regarding the selection of energy saving technologies.

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[4] Load factor is the ratio of the average load over a designated period of time to the peak load occurring during that period.

A thermo-economic[5] analysis of cogeneration systems was presented for three existing cogeneration plants in France (Benelmir and Feidt, 1998). It was found that cogeneration systems are not operated following an efficient energy management procedure but rather constrained by the very complex electricity utility cost rate strategy. It was concluded that the cogeneration systems studied will not be competitive with a conventional system if they were operated at some tariffing modes and that the lifetime of the equipment has an impact on the profitability of the system.

A optimal operational planning system was developed using an object-oriented framework for the purpose of determining operational strategies of energy supply plants (Kamimura *et al.*, 1999). An energy flow diagram was used to illustrate the energy flow from supplies to demand via equipment, where energy balance and supply-demand relationships were formulated for each energy flow based on the first law of thermodynamics. Variables expressing the operational strategies composed of continuous and binary variables were described, which correspond to the energy flow rates and the on/off status of operation, respectively. Linear relationships between flow rates of input and output energy are formulated using the defined variables. Binary variables were employed to consider the discontinuity of performance characteristics due to on/off status and the linear equations expressed a change of efficiency due to rate/part load status. The objective function of the optimization problem was formulated by using both binary and continuous variables. The optimization problem resulted in a mixed-integer linear programming problem and it could be solved by using the branch and bound method along with the dual simplex method. According to the formulation, the matrix for the simplex tableau was generated as input data for solving the mixed-integer linear programming problem and the optimization calculation was carried out to find the optimal values of variables expressing the operational strategy.

To address the problem of shiftable loads[6], a model was developed for optimal energy management with minimum costs which included a scheduling tool that was built into the model to help in the scheduling of multi-interval shiftable loads with variable amplitude load profiles (Venkatesh and Chankong, 1995). A mixed integer program was used to develop the model

[5] Thermo-economic studies refers to studies using the principles of exergy analysis and cost-objective function optimization.
[6] Shiftable loads term refers to variable loads, such as those resulting from laboratory experiments.

which could be used for applications of multi-plant cogeneration systems (gas turbine and steam turbine) operating in either topping or bottoming cycles. One of the assumptions made in the model was that the efficiency of the various components in a cogeneration plant increased with increasing operating load. This assumption was not valid for most of the cogeneration systems and the relationship of the efficiencies of equipment and operating load was non-linear. Although the authors acknowledge that such an assumption impacts the accuracy of the results, the thermodynamic model was still built on the assumption of linearity.

Few studies addressed the issue of environmental impacts using thermo-economic optimization with regards to cost and $CO_2$ emissions. (Burer *et al.*, 2003) developed a thermo-economic optimization with regards to cost and $CO_2$ emission rates for the design and operation of district heating, cooling and power generation unit composed of an solid oxide fuel cell and gas turbine (SOFC-GT) combined cycle, associated with a heat pump, a compression chiller and/or absorption chiller, and an additional gas boiler. A Pareto optimal frontier was derived, which defines the minimum cost required to achieve any level of $CO_2$ emissions with a given technology or inversely the maximum $CO_2$ emissions abatement achievable with a given financial effort. Decision variables related to the SOFC/GT that were chosen for optimization were the amount of fuel provided to the SOFC, the working temperature and pressure of the SOFC and the pinches at the final heat recovery devices. Other decision variables, related to the heat pump and the absorption chiller included the nominal capacity of the heat pump (winter), the ratio between the summer part load and nominal load, and the ratio between the mid season part load and nominal part load of the heat pump, while decision variables for the absorption chiller included the type of the chiller, its capacity, and its operating conditions. Although the model considered part load characteristics of the heat pump and absorption chillers in the design, hourly variations in thermal demand were considered to be covered by the thermal storage device. The power load was also assumed to be constant in the three modeled seasons, and the power generation unit was considered to be working at nominal load all along the year. Findings from the study show that SOFC-GT systems associated with a heat pump and chillers cut $CO_2$ emissions by half compared to current technologies. The advantage of this model was that a multi-objective algorithm was used to solve non-linear mixed integer problems by using the Pareto-optimal frontiers which did not drive to a single optimum, but allow for the identification of multiple solutions. This methodology was useful when considering technical, economic as well as environmental factors in the design of cogeneration applications.

An energy equilibrium model was used to study conventional systems and cogeneration-based district energy (DE) systems for providing heating, cooling, and electrical services to assess the potential economic and environmental benefits of cogeneration-based DE systems and to develop optimal configurations (Wu and Rosen, 1999). The energy equilibrium model integrated the theoretical and analytical methods of several disciplines, including engineering (especially process analysis), economics, and operations research. Among these disciplines, models were based on economic theory tend a customer behavioral description on the demand side, while models of the engineering processes tended to be concerned with the production and technical aspects of the supply activities. The energy equilibrium formulation combined the two approaches in which the evolution of a market can be analyzed under various assumptions regarding production technologies and consumption behavior, and the formulation and evaluation of various policies and plans can be carried out with explicit recognition of both technical constraints and customer response. In the energy equilibrium model, supply was represented by a cost-minimizing linear model and demand by a vector-valued function of prices, taking discount factors per period into consideration. They used software (WATEMS) to formulate and solve the energy equilibrium model which employed sequential non-linear programming to calculate a spatial inter-temporal equilibrium of energy supply and demand. The authors considered two evaluation methods for the analysis of the economic impacts: analysis of the present worth of partial social welfare change and analysis of payback period. For the environmental impacts, the authors presented the $CO_2$ emission measures to either evaluate the $CO_2$ emission levels over the time horizon of the model for a given energy policy or scenario or evaluate $CO_2$ the emission levels constrained within upper limits. The paper included a case study for illustration of the model, and the authors recommended considering cogeneration-based DE systems among the options for meeting heating, cooling, and electric power needs for their potential economic and environmental advantages over conventional systems. This model is a very useful approach for decision making when forecasting the role of cogeneration technologies in future applications and also for the analysis of social response to such applications.

Operations research techniques were used to optimize the operation of cogeneration systems and examine their performance using approaches other than mixed integer linear programming. For instance, an optimization model was developed for cogeneration with a gas engine generator using a Hamiltonian algorithm (HA) where the results indicated that the HA was effective in designing the optimal cogeneration system and controlling the operation of these systems under an economic objective function including investment in the plants and equipment (Yanagi *et al.*, 1999). The Hamiltonian algorithm is based on newly proposed information processing technique called higher dimensioning because it utilizes the properties of motion in a dynamic system consisting of many particles. Given the objective function, the HA expresses the change in the value of the function in terms of the motion experienced by a dynamic system having N degrees of freedom corresponding to N variables. By using the properties of this motion, the algorithm speeds up the search for an optimum value by generating autonomous motion in the dynamic system in search of the optimum value of the objective function. The HA obtained the desired solution by adding conjugate variables to control variables and increasing the degrees of freedom of the system (creating a high-dimension system) with the aim of promoting autonomous movement between variables.

The validity of an equation-oriented (EO) mathematical model for the optimization of heat and power systems was examined using a sequential quadratic programming (SQP) method called filterSQP (Rodriguez-Toral *et al.*, 2000). A combination of simple unit operations and an actual whole real cogeneration plant with a commercial gas turbine were used to demonstrate the applicability of the combined cycle cogeneration plants (CCCP) model and the modeling package. Findings from the study validated the effectiveness of the EO model and the EO infrastructure for simulation and optimization of real CCCPs.

An energy process model with a geometric distributed lag demand[7] (GDL) process was used to examine the feasibility, economic impacts and identification of the necessary structural changes in the energy system of North America to reduce $CO_2$ emissions to the target levels for 2005 and 2030 (Chung *et al.*, 1997). The model was formulated and solved with the Waterloo Energy Modeling System (WATEMS), which uses a decoupling algorithm to calculate inter-

[7] GDL represent the time lagged effect in the demand side wherein the energy GDL process model, the demand is a represented by a function of prices, not only in the current time period but also in previous time periods and the supply is a cost-minimizing linear process submodel.

temporal energy equilibrium of energy supplies and demands of oil, gas, and coal (define) in Canada and the USA. The energy GDL process was used to evaluate the impacts of controls on $CO_2$ emissions, which takes into consideration the time-lagged effect by considering the consumers' response to prices. In the energy GDL process model, the demand was represented by a function of the prices, not only in the current time period but also in previous time periods based on the GDL structure, and the supply is a cost-minimizing linear process sub-model. The time-lagged effect was represented through the GDL mechanism only in the demand sub-model but not in the supply sub-model. The time-lagged effects on the supply side were represented through constraints such as those which force new production capacity to continue into the future until retirement age (at a declining rate of production in the cases of oil and gas). Results from the model showed that a delay in launching a $CO_2$ emission control program could be very costly, and, given the current array of fuels, supply technologies and consumer response, it seems impossible to reach the International Conference in Toronto targets, i.e., reducing to 50% below the 1988 $CO_2$ emission levels by 2030.

## 2.5 SUMMARY

The available studies in the literature that use operations research techniques focus their objectives on economic implications and lack modeling of the design and operation of energy systems based on their environmental impacts. The focuses of the studies on cogeneration systems are limited to gas and steam turbines (Marechal and Kalitventzeff, 1998; Venkatesh and Chankong, 1995) with the exception of one study that investigated the optimization of solid oxide fuel cell and gas turbine combined cycle with regards to cost and emission rates (Burer et al., 2003). Within those studies the environmental impacts that are addressed are limited to the assessment of the carbon dioxide emissions resulting from the operation of these systems (Chung et al., 1997; Wu and Rosen, 1999; and Burer et al., 2003).

Several studies relating to the application of CHP technologies were performed to investigate the optimum operational strategies mainly from the efficiency and economic perspectives; however, these studies have used other approaches rather than operations research techniques to model their systems, or used existing CHP systems (Fawkes et al., 1998; Jones, 1999; Gunes, 2001; Marantan et al., 2002; Jalalzadeh et al., 2002; Yodovard et al., 2001; Ellis and Gunes, 2002).

Few LCA studies available in the literature address the application of cogeneration systems in buildings. The LCA studies include the assessment of the environmental impacts resulting from various electric generation systems (Michaelis, 1998; Gagnon et al., 2002), natural gas combined cycle (NGCC) (Spath and Mann, 2000; Lombardi, 2003), and solid oxide fuel cell cogeneration system (Pehnt, 2003)

Despite the range of modeling options available in the literature, a gap exists. By using a combination of energy simulation, operations research techniques, and an LCA approach to model various energy processes, a model and framework is developed in this work to assess the potential life cycle environmental impact of the application of cogeneration systems in buildings. In addition, the model would integrate conventional energy systems with cogeneration system applications in buildings and optimize their operation while considering the thermodynamic characteristics of these systems in order to achieve a certain objective such as minimizing life cycle emissions.

Hourly energy simulation will be used to generate the electrical and thermal energy use of a building. Hourly energy simulation rather than annual energy simulation provides more insight on the fluctuations in energy demand during a day, e.g., peak versus non-peak hours, as well as seasonal change in energy demand, e.g., summer versus winter. An earlier study that has used an LCA approach to model cogeneration system applications in commercial buildings showed that the performance of a cogeneration system is generally affected by a building's load characteristics and the electric and thermal efficiency ratios of a cogeneration process, which determines the quantity of electricity and heat that is generated from these processes and that the preferred cogeneration system, e.g., solid oxide fuel cell (SOFC) or internal combustion engine (ICE), varied if the energy demand was modeled annually versus hourly (Osman, 2002).

An LCA approach is used to model the energy systems to encompass all the upstream and downstream processes associated with the production and use of energy. This approach will help in analyzing the performance of energy systems by considering the different product's life stages and their impact on the environment. The environmental impacts can be global such as greenhouse gases, regional, such as acid rain, or local, such as smog formation. By taking all these parameters into consideration, a more comprehensive environmental impact assessment can be achieved rather than considering a single parameter such as carbon dioxide emissions. In addition, by using an LCA approach to model different energy systems, the results could be used to predict the performance of cogeneration systems in various applications, such as variable energy use due to size and occupancy of buildings and/or different climates.

To consider the different operational strategies that are available for the operation of cogeneration systems, which can vary from hour to hour, in addition to integrating grid-based energy systems and cooling and heating energy options, mixed integer linear programming is used. Linear programming is an effective tool for determining the values of a set of decisions, such as power from a cogeneration unit at a specific hour, which can take on a large set of possible values, in order to optimize a linear objective function, such as minimum global warming potential.

The LCA optimization models developed consider the following cogeneration systems: an internal combustion engine (ICE), a microturbine (MT), and solid oxide fuel cell (SOFC). These systems are chosen to assess the performance of the available cogeneration technologies, in terms of environmental impacts, when used in building applications. The efficiencies of these energy systems directly impact the consumption of primary energy resources as well as the emissions resulting from their use. LCA software is used to model these systems and the models include their efficiencies, auxiliary materials and auxiliary energy use and emissions. Furthermore, grid-based energy systems including the average USA electric generation mix and natural gas combined cycle (NGCC) power plants representing conventional electric generation options are modeled and integrated into the optimization model. A gas boiler is modeled to present a conventional heating option (other than heating from cogeneration systems). Two cooling systems are also considered in the optimization model formulation: absorption and electric chillers.

Lastly, part-load models for cogeneration systems are developed to analyze their performance at different part load operations, as the systems' efficiencies vary with part load operations.  The objective of developing the LCA optimization model is to predict the most effective energy system options including cogeneration systems and utility power options that are economical and can result in the minimum life cycle environmental impacts.

## 3.0 LIFE CYCLE ASSESSMENT

### 3.1 INTRODUCTION

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., cradle-to-grave) from raw material acquisition through production, use and disposal. According to the American National Standards Institution and International Standards Organization (ANSI/ISO, 1997), the LCA phases include definition of goal and scope, inventory analysis, impact assessment, and interpretation, as shown in Figure 3-1.

The phases of an LCA as defined by ANSI/ISO (1997) are:

I. *Goal of the study*: The goal of the LCA study should state the intended application, the reasons for carrying out the study and the intended audience.

II. *Scope of the study*: The scope of the study should describe:

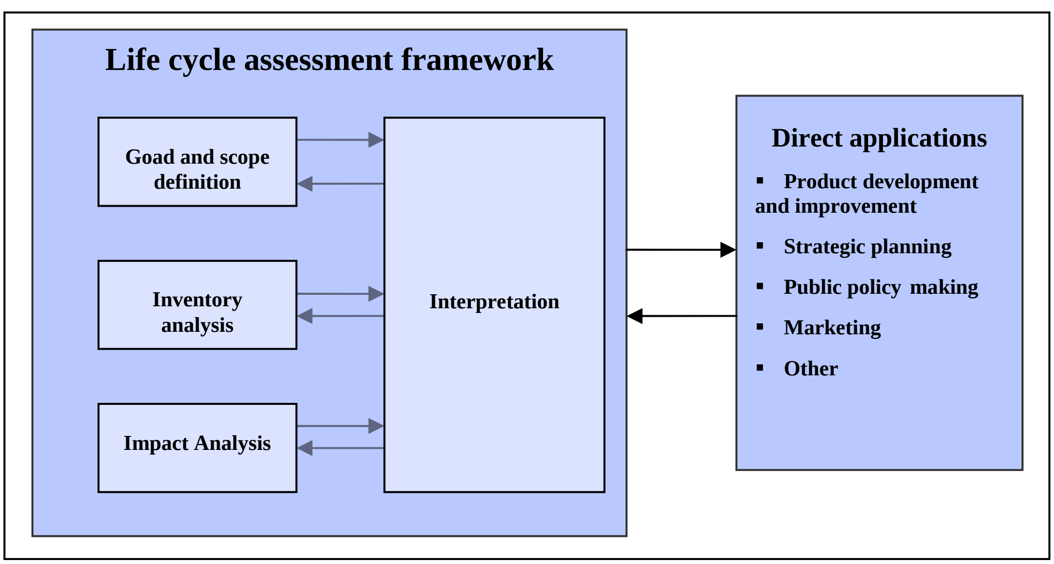



**Figure 3-1: Life cycle assessment framework (ANSI/ISO, 1997).**

- The product system to be studied;
- The functions of the product system or systems;
- The functional unit: The functional unit is a measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. The reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis;
- The product system boundaries: The system boundaries determine which unit processes shall be included within the LCA. Several factors determine the system boundaries, including the intended application of the study, the assumption made, cut-off criteria, data and cost constraints, and the intended audience. The selection of inputs and outputs, the level of aggregation within a data category, and the modeling of the system shall be consistent with the goal of the study. The system should be modeled in such a manner that inputs and outputs at its boundaries are elementary flows. The criteria used in establishing they system boundaries shall be identified and justified in the scope of the study;
- Allocation procedures: Allocation procedures are needed when dealing with systems involving multiple products. The materials and energy flows as well as associated environmental releases shall be allocated to the different products according to clearly stated procedures, which shall be documented and justified;
- Types of impact and methodology of impact assessment, and subsequent interpretation to be used;
- Assumptions;

- Limitations: Some of the limitations present in LCA studies may include: the subjective nature of choices and assumptions made in the LCA. The models used for inventory analysis or to assess environmental impacts are limited by their assumptions, and may not be available for potential impacts or applications. The results of LCA studies focused on global and regional issues may not be appropriate for local applications; The accuracy of LCA studies may not be limited by accessibility or availability of relevant data, or data quality, i.e., gaps, aggregation, average, site-specific etc.; and the lack of spatial and temporal dimensions in the inventory data used for impact assessment introduces uncertainty in impact results. This uncertainty varies with the spatial and temporal characteristics of each impact category;
- Data requirements: Data quality requirements specify in general terms the characteristics of the data needed for the study. Data quality requirements shall be defined to enable the goals and scope of the LCA study to be met. The data quality requirements should include:

(a) Time related coverage;

(b) Geographical coverage;

(c) Technology coverage;

(d) Precision: measure of variability of the data values for each data category expressed (ISO, 1998);

(e) Completeness: percentage of locations reporting primary data from the potential number in existence for each data category in a unit process;

(f) Representativeness of the data: qualitative assessment of the degree to which the data set reflects the true population of interest;

(g) Consistency: qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;

(h) Reproducibility of the methods used throughout the LCA: qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reports in the study;

(i) Uncertainty of the information;

(j) Critical review, which is a technique to verify whether an LCA study has met the requirements of the international standard methodology, data and reporting. Whether

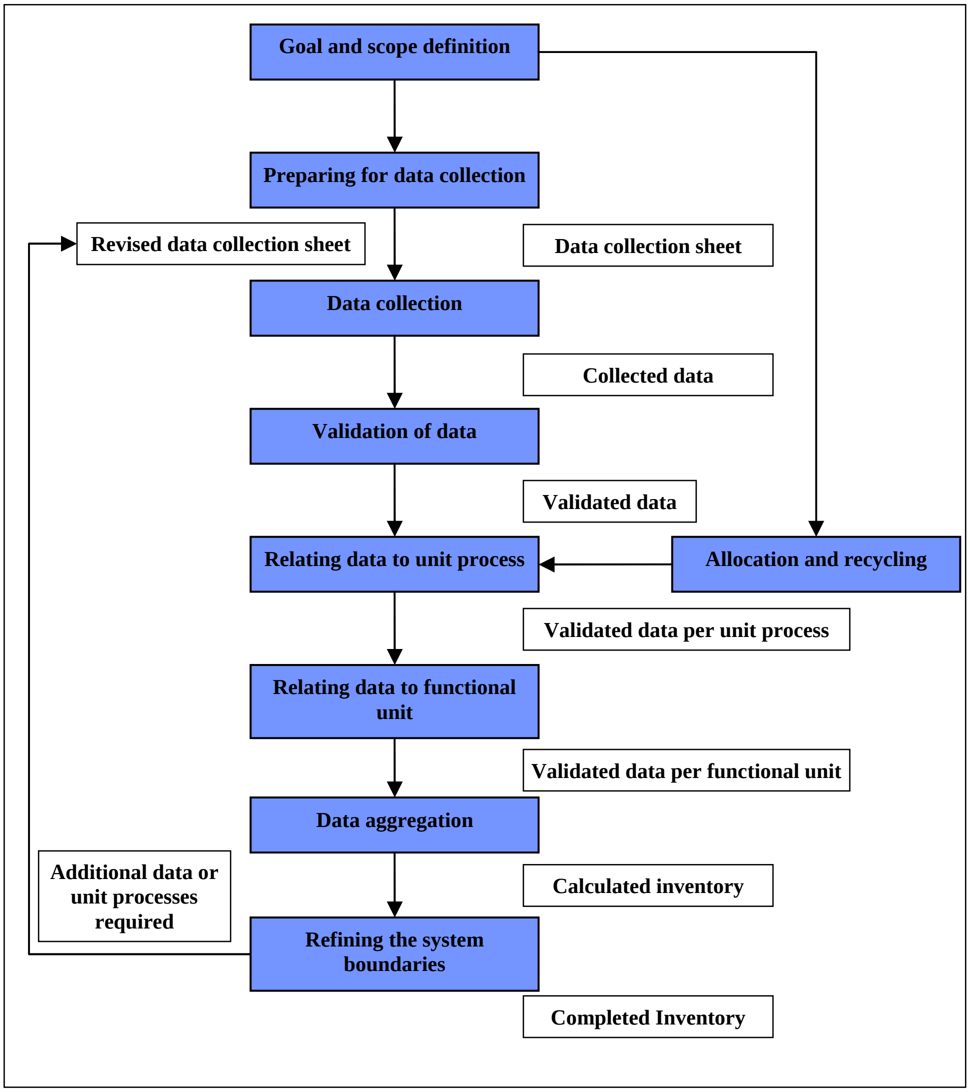



**Figure 3-2: Inventory analysis step (ANSI/ISO, 1997).**

and how to conduct a critical review, as well as who conducts the review, shall be in the scope of the study;

(k) Finally, the type and format of the report required for the study, which shall be fairly, completely and accurately reported to the intended audience.

III. *Life cycle inventory (LCI) analysis*: The inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of the product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system. Interpretations may be drawn from these data, depending on the goal and scope of the LCA. These data also constitute the input to the life cycle impact assessment. The qualitative and quantitative data for the inclusion in the inventory is collected for each unit process that is included within the system boundaries. Practical constraints on data collection should be considered in the scope and documented in the study report. Some significant calculation considerations are: allocation procedures, and the calculation of the energy flow, which should take into account the different fuels and electricity sources used, the efficiency of conversion and distribution of the energy flow as well as the inputs and outputs associated with the generation and use of that energy flow (ANSI/ISO, 1997). The operational steps that should be performed for inventory analysis are outlined in Figure 3-2.

IV. *Life impact assessment*: According to ANSI/ISO (1997), the impact assessment phase of the LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts and attempting to understand those impacts. The level of detail, choice of impacts evaluated and methodologies used depend on the goal and scope of the study. The impact assessment phase may include elements such as: assigning of inventory data to impact categories (classification); modeling of the inventory data within impact categories (characterization); and possibly aggregating the results in very specific cases and only when meaningful (weighting).

The methodological and scientific framework for impact assessment is still being developed. There are no generally accepted methodologies for consistently and accurately associating inventory data with specific potential environmental impacts. Thus, this step is subjective and depends on the choice, modeling, and evaluation of the impact categories.

V. *Life Cycle Interpretation*: Interpretation of the LCA in which findings from the inventory analysis and impact assessment are combined together in a way consistent with the defined goal and scope in order to reach conclusions and recommendations.

The LCA framework provides a tool to understand and analyze the performance of energy systems by considering the different products' life stages and their potential impact on the environment. Some of the significant factors that impact the assessment of energy systems application in buildings are: energy resource use, the electrical and thermal efficiencies of these processes, and the load requirements of buildings. The choice of fuel will impact the emissions resulting from its use. For instance, natural gas combustion, which is the primary fuel of use in cogeneration systems, will result in lower emission releases of carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide and particulates compared to emissions resulting from coal and oil combustion. Refer to Table 3-1 for typical emissions resulting from the combustion of different fuel sources (EIA, 1999). In addition, the efficiencies of combustion and transfer of energy varies between centrally located utility plants, as is the case of the production of electricity from a mix of power plants in the USA, versus cogeneration plants which are usually located on-site and used to meet specific load requirements. The load requirements of buildings have a direct effect on the environmental impacts resulting from the use of cogeneration systems. For instance, cogeneration systems that have low thermal efficiency factor may not be appropriate for use in buildings with high thermal load requirements. The potential environmental impacts resulting from the application of energy systems in buildings can be global such as greenhouse gases, regional, such as acid rain, or local, such as smog formation.

**Table 3-1: Typical emissions resulting from fuel combustion (EIA, 1999).**

| Pollutant | Natural Gas | Oil | Coal |
|---|---|---|---|
| *Pounds of air pollutants produced per billion BTU of energy* | | | |
| **Carbon Dioxide** | 1.17 E+06 | 1.64 E+06 | 2.08E+06 |
| **Carbon Monoxide** | 4.00 E+01 | 3.30 E+01 | 2.08 E+02 |
| **Nitrogen Oxides** | 9.20 E+01 | 4.48 E+03 | 4.57 E+03 |
| **Sulfur Dioxide** | 1.00 E+00 | 1.12 E+03 | 2.59 E+03 |
| **Particulates** | 7.00 E+00 | 8.40 E+01 | 2.74 E+03 |
| **Mercury** | 0.00 E+00 | 7.00 E-03 | 1.60 E-02 |

## 3.2 GOAL AND SCOPE OF THE LCA STUDY

The goal of the LCA study is to create models of grid-based energy systems, cogeneration systems, and heating and cooling systems. The objective of developing these models is to assess the potential environmental impact associated with the different stages in the production of energy and manufacturing of energy systems as well as their use in buildings.

### 3.2.1 System Boundaries

The scope of the LCA study covers the following systems:

- Conventional USA average electric generation mix;
- Natural gas combined cycle (NGCC) power plant;
- Solid oxide fuel cell (SOFC) cogeneration system;
- Microturbine (MT) cogeneration system;
- Internal combustion engine (ICE) cogeneration system; and
- Gas boiler.

Following the ANSI/ISO guidelines, the environmental impact categories chosen to quantify the potential environmental impact of input and output from the life cycle inventory of these systems are:

- Global Warming Potential (GWP),
- Acidification Potential (AP),
- Tropospheric Ozone Precursors Potential (TOPP), and
- Primary Energy Consumption (PE)

A detailed description of the life cycle environmental impact categories and the calculations used in characterization of the inventory data is given in Section 3.4. Interpretation of the LCA results is given in Section 3.5.

The energy systems are modeled to assess the potential environmental impacts throughout their life cycle that might result from their use in meeting the electrical, heating, and cooling in commercial buildings. The intended use of the LCA analysis is to investigate the operational characteristics of these systems by considering their potential environmental impacts to improve building design. The life stages included in the LCA model development are: extraction of raw materials and energy resources, transportation, production, combustion/conversion, and use.

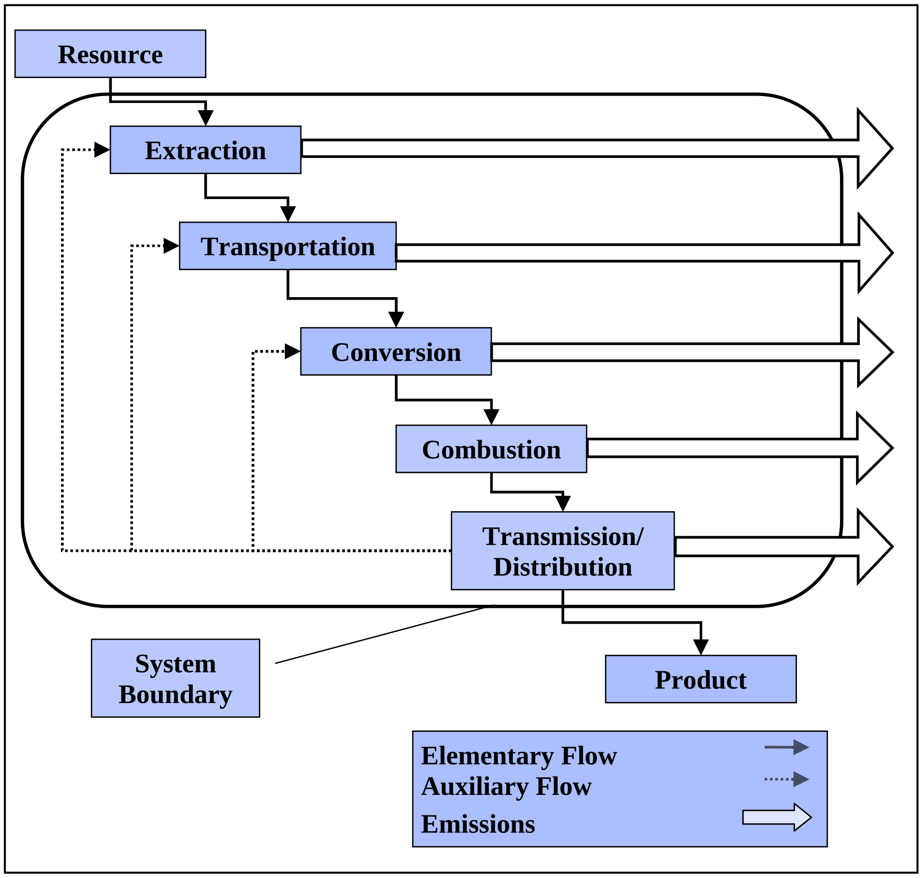



**Figure 3-3: Example of a product system.**

Data required for creating the LCA models of these systems encompass primary and secondary raw materials and energy resources associated with the processes and air emissions resulting from the different stages in the life cycle of these systems. The unit processes are linked together by elementary flows: raw materials and energy entering the processes from the environment, and materials and energy leaving the processes, which are discarded into the environment. Within the system boundaries, processes are linked together by intermediate product flows, such as auxiliary materials required for construction, auxiliary energy required for operating the process, and transportation required to deliver auxiliary materials/energy to the process. An example of a product system is given in Figure 3-3.

### 3.2.2 Assumptions & Limitations

The assumptions considered in developing the LCA models for the energy systems under investigation are:

- Elementary flow at system boundaries considered.
- Technology specifications.
- With respect to geographical and time coverage, this study assesses the current and near future development of cogeneration systems in the USA. Average electric generation mix is modeled based on current description of electric production in the USA.
- Thermal and electric conversion efficiencies of the cogeneration systems are achievable.
- Cogeneration systems are capable of following a specific thermal or electrical load of the building.
- The thermal and electric energy produced from the cogeneration processes is of utilizable quality.
- No heat or electric loses from the cogeneration processes are considered other than those captured by the conversion efficiencies.
- No credit is taken for any electrical or thermal energy generated above the demand.
- Some of the data used in the model are average data, such as USA average electric generation mix, which is not characteristic of a specific location.

One of the limitations of this LCA study is that the environmental impact indicators used are not representative of comprehensive environmental impact analysis but represent a class of potential environmental impacts representing a global impact category such as global warming potential (GWP), local impact such as tropospheric ozone precursors potential (TOPP), regional impact such as acidification potential (AP), and an impact that transcends from local to regional and global impact such as primary energy consumption (PEC). These impact categories represent widely used environmental parameters, which could be used for comparative analysis with previous and future studies.

A comprehensive environmental impact analysis would be more valuable if the study is done on an actual setting; however, because the current study is used in a hypothetical building, the results could provide a general understanding of the performance of energy systems in buildings and ways to minimize the environmental impacts of their use. Some of the principal environmental impact indicators not addressed in this study are human toxicity, ecological toxicity, particulates formation, indoor air quality, and land use.

Data used for creating the LCA models are based on information collected from literature and not from personal experimental and field measurements of actual settings. Although there is a high confidence in these data, consideration should be taken that the studied systems might behave differently in real settings especially with certain cogeneration systems that are influenced by climate characteristics of the location of use.

Future market analysis and social behavior patterns towards the implications of adopting cogeneration systems instead of the current conventional practice is not considered because it is out of the scope of the research objectives.

### 3.2.3 Functional Unit

The functional unit that is used to measure the performance of the functional outputs of the energy systems modeled in this study is the production of 1-kWh of energy output. A kWh of *electric* energy output is used as the functional unit for the following processes: cogeneration systems (SOFC, ICE, and MT), average electric generation mix and NGCC. A kWh or 3.421E-03 MMBTU of *thermal* energy output is used as the functional unit for the gas boiler.

## 3.3 INVENTORY ANALYSIS

Data from the literature and commercially available systems, such as boilers, chillers, and cogeneration systems, are used to define the characteristics of the modeled unit processes, such as energy efficiencies, sizes, weights, compositions, emissions etc. LCA software, GEMIS, is used to model the energy systems by defining the characteristics of each *unit process*, e.g. SOFC anode, SOFC cathode etc., and constructing a *product system*, e.g. SOFC cogeneration unit, by linking the various major unit processes through a product's flow across the system's boundaries, such as energy flow, the intermediate product flow within the system boundaries, such as auxiliary energy flow, and an elementary flow to the environment, both entering a unit process, such as natural gas, and leaving a unit process, such as air emissions.

The LCI includes all processes associated with the unit processes, such as extraction, transportation, conversion and combustion of fuels/materials and distribution/transmission of resources. The LCI consists of inputs and outputs of materials, energy resources, and emissions associated with each of the modeled energy systems: SOFC cogeneration system, ICE cogeneration system, MT cogeneration system, USA average electric generation mix, NGCC, and gas boiler.

The GEMIS database is used to construct the LCI for the following processes:

- the USA average electric generation,
- primary energy resources including renewable and non-renewable resources, such as natural gas, coal, geothermal, hydropower, and wind, and
- raw materials, such as metals and minerals.

A detailed description of the LCI of the modeled energy systems follows.

### 3.3.1 Natural Gas Production

Natural gas is used as the fuel for fueling cogeneration systems, the NGCC power plant, gas boilers and the USA natural gas-fired gas turbine power plant. The GEMIS database is used to create the LCI data on the extraction, transportation, processing, and distribution of natural gas. The life cycle stages that are modeled in the natural gas production process are illustrated in Figure 3-4.

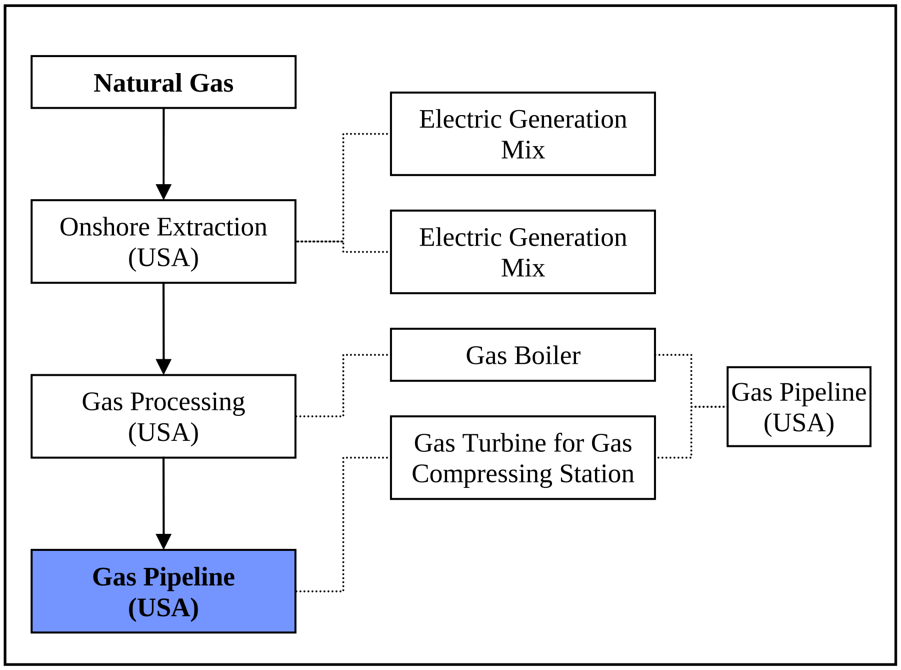



**Figure 3-4: Life cycle stage for natural gas production.**

Table 3-2 shows the content of natural gas modeled based on the GEMIS database. Table 3-3 shows the characteristics of the life cycle stages for natural gas production including gas extraction, processing, transportation processes. Also, Table 3-3 includes the characteristics of the gas turbine compressor process which is used in the gas pipeline and converts natural gas from the pipeline to mechanical power.

**Table 3-2: Natural gas fuel content (GEMIS database)**

| Content | %Volume |
|---|---|
| **$CH_4$** | 92.0695 |
| **$C_2H_6$** | 0.5 |
| **$C_2H_4$** | 0.5 |
| **$C_3H_8$** | 0.04 |
| **$C_4H_{10}$ ^n^** | 0.01 |
| **$C_4H_{10}$ ^i^** | 0.01 |
| **$CO_2$** | 0.02 |
| **$N_2$** | 6.1 |
| **$H_2S$** | 0.0005 |
| **$H_2$** | 0.75 |
| **LHV** | 33.80124 (MJ/Nm$^3$)<br>44.79037 (MJ/kg) |
| **HHV** | 37.49271 (MJ/Nm$^3$)<br>49.68197 (MJ/kg) |

**Table 3-3: Life cycle stages of natural gas production.**

| Life cycle stage | Size (kW) | Process Efficiency (%) | Operating Hours (hrs/year) | Life-time (years) | Auxiliary Energy[a] kWh/kWh | Auxiliary Materials[b] kg/MW | Emissions (lb/MMBTU) |
|---|---|---|---|---|---|---|---|
| Gas Extraction | 1.0E+06 | 100 | 7000 | 20 | Electric: 1.1E-03 | Steel:1.0E+04 Cement:1.50 E+04 | $CH_4$: 5.58E-02 |
| Gas Processing[c] | 1.0E+06 | 100 | 7000 | 20 | Electric: 1.0E-03 Heat: 1.0E-03 | Steel: 3.0E+04 Cement: 6.0 E+04 | $CH_4$: 5.58E-02 |
| Gas Pipeline[d] | 10E+06 | - | 7500 | 30 | - | Steel: 2.4E+05 Sand: 1.0E+06 | $CH_4$: 4.38E-03 $CO_2$: 2.61E-06 $H_2S$: 5.08E-08 NMVOC: 9.51E-05 |
| Gas Turbine Compressor[e] | 10E+03 | 30 | 5000 | 15 | - | Steel: 2.5E+04 Cement: 6.5E+04 | $CH_4$: 3.26E-02 $CO_2$: 427.62 $SO_2$: 3.32E-03 NMVOC: 6.51E-02 $NO_X$: 2.28 $N_2O$: 1.95E-02 CO: 6.51E-01 Particulates: 3.26E-02 |

[a] Auxiliary energy is the energy required by the unit process.
[b] Auxiliary materials are the materials required for the construction of the unit process.
[c] No desulphurization is assumed and 0.125% of throughput is assumed for direct emissions of CH4.
[d] Gas pipeline width is 5 meters, length 1.6E+03 km, transport energy of 269E-03 MJ/t.km, and losses 600E-06%/100km.
[e] No NOx control is considered. Flue gas condition is 15% O2 by volume, CO2 content is 3.22% by volume, and the stack height is 10 meters. Emissions are based on fuel output.

### 3.3.2 USA average electric generation mix

The electric generation mix in the USA consists of: 53% Coal, 17% Natural Gas, 17% Nuclear, 9% Hydro, 2% Oil, 2% Waste, 0.4% Geothermal and 0.15% wind (International Energy Agency, 1998). Also, an average grid loss of 6.5% is assumed in the process (EIA, 2002). The life cycle stages included in creating the LCA model for the average electric generation mix using the GEMIS database are given in Table 3-4, which include size, conversion efficiencies, operating hours and lifetime of the life cycle stage of electric production processes. The electric conversion efficiency of the electric generation mix is 32% based on the low heat value (LHV) of fuel input. An illustration of the life cycle stages for the average electric generation mix in the USA are shown in Figure 3-5. Table 3-5 shows the life cycle stages of processes associated with oil extraction and Fig 3-6 illustrates these stages. Table 3-6 shows the emission factors used in the LCI of the life cycle stages in power production.

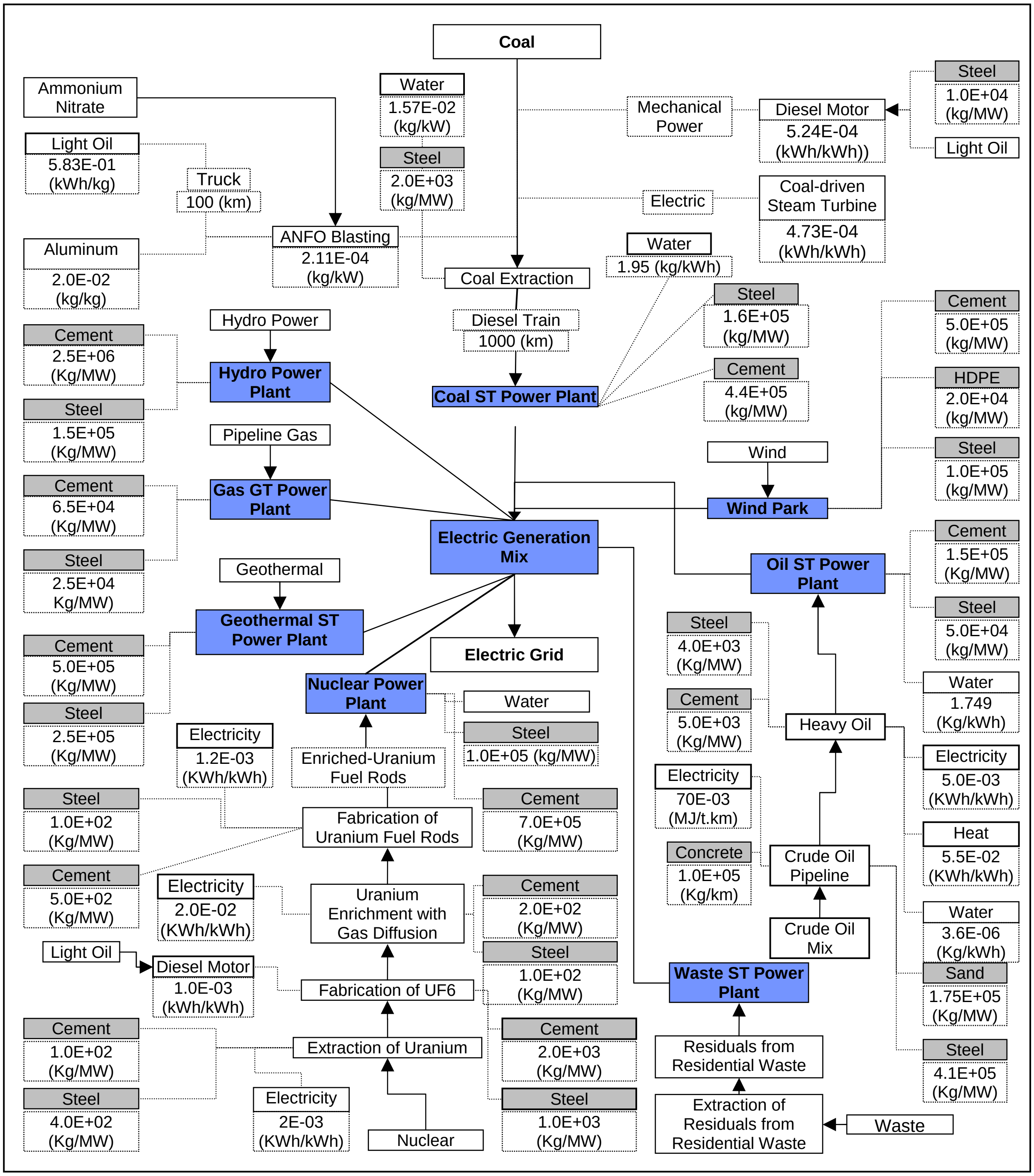



**Figure 3-5: Life cycle stages for average electric generation.**

**Table 3-4: Life cycle stages for average electric generation.**

| Power Plant | Life Cycle Stage | Size (MW) | Conversion Efficiency (%) | Operating Hours (hrs/year) | Lifetime (years) |
|---|---|---|---|---|---|
| Coal–fired ST Power Plant | Coal-fired ST Power Plant | 500 | Coal to electric power: 37 | 5000 | 25 |
| | Coal Extraction a | 1500 | Coal mining: 100 | 7000 | 20 |
| | Motor Diesel | 1 | Fuel to mechanical power: 30 | 2500 | 10 |
| | Explosives (ANFO Blasting) b | - | Ammonium nitrate to explosives: 108 | 5000 | 20 |
| Natural Gas GT | Natural Gas Turbine Power Plant c | 50 | Natural gas to electric power: 35 | 1000 | 15 |
| Oil-fired ST Power Plant | Oil-fired ST Power Plant | 450 | Refined heavy oil to electric power: 41 | 4500 | 20 |
| | Refinery for Oil | 2000 | Crude oil to heavy oil: 99.5 | 7000 | 20 |
| | Crude Oil Offshore Transportation by Pipeline (length: 500 km) | 37000 | - | 7500 | 15 |
| | Primary offshore oil extraction in the USA | 1500 | Oil resource to crude oil: 100 | 7000 | 25 |
| | Secondary offshore oil extraction in the USA | 1500 | Oil resource to crude oil: 100 | 700 | 25 |
| | Tertiary onshore oil extraction in the USA | 1000 | oil resource to crude oil: 100 | 7000 | 25 |
| | Primary and Secondary onshore oil extraction in the OPEC countries | 1500 | 94.4 | 7000 | 25 |
| Nuclear Power Plant | Nuclear Power Plant | 1250 | Fuel to electric power: 33 | 6500 | 25 |
| | Uranium Fuel Rods Manufacturing | 1500 | Enriched uranium to fuel rods: 100 | 6000 | 20 |
| | Enriched Uranium Production with Gas Diffusion | 1500 | 100 | 7000 | 20 |
| | UF6 c | 1500 | Extracted uranium to UF6: 100 | 7000 | 20 |
| | Uranium Extraction | 1500 | Nuclear resource to Uranium: 100 | 7000 | 20 |
| | Waste-fired ST Power Plant | 10 | Residential residual waste to electric power: 12.5 | 6600 | 15 |
| | Hydro Power Plant | 1000 | Hydro to electric power: 100 | 5000 | 50 |
| | Geothermal ST Power Plant | 100 | Geothermal to electric power: 100 | 5000 | 20 |
| | Wind Turbines Park | 1 | Wind to electric power: 100 | 2500 | 20 |

The coal extraction process is modeled to include both deep and surface coal mining
UF6 uranium yellowcake and uranium hexafluoride
Wind turbines park consists of 100 kW units turbines.

**Table 3-5: Life cycle stages for oil production.**

| Life cycle stage | Oil Mix Share (%) | | Auxiliary Energy (kWh/kWh) | Auxiliary Construction Material (kg/MW) | Emissions (lb/MMBTU) |
|---|---|---|---|---|---|
| Primary Offshore Oil Extraction | 25 | | Electric: 1.1E-03<br>Mechanical: 2.0E-02<br>Process Heat: 2.3E-03 | Steel: 6.1E+04<br>Cement: 5.1E+04 | $CH_4$: 1.16E-01<br>$CO_2$: 6.05E-01<br>NMVOC: 2.79E-03 |
| Secondary Offshore Oil Extraction | 25 | | Electric: 3.0E-03<br>Mechanical: 2.0E-03<br>Process Heat: 2.3E-03 | Steel: 6.1E+04<br>Cement: 5.1E+04 | $CH_4$: 1.19E-01<br>$CO_2$: 6.05E-01<br>NMVOC: 6.98E-03 |
| Tertiary Onshore Oil Extraction | 10 | | Electric: 5.0E-03<br>Process Heat: 1.0E-01 | Steel: 8.0E+03<br>Cement: 3.0E+03 | $CH_4$: 4.65E-03<br>NMVOC: 6.98E-03 |
| OPEC Oil Mix | 40 | Onshore Primary Crude Oil Extraction (80%) | Mechanical: 2.0E-03<br>Process Heat: 5.0E-03 | Steel: 1.0E+04<br>Cement: 9.0E+03 | $CH_4$: 2.26E-01<br>$CO_2$: 1.602E+00<br>NMVOC: 6.59E-02 |
| | | Onshore Secondary Crude Oil Extraction (20%) | Mechanical: 2.0E-03<br>Process Heat: 5.0E-03 | Steel: 6.0E+04<br>Cement: 5.2E+03 | $CH_4$: 1.14E-02<br>$CO_2$: 1.602E+00<br>NMVOC: 6.59E-02 |

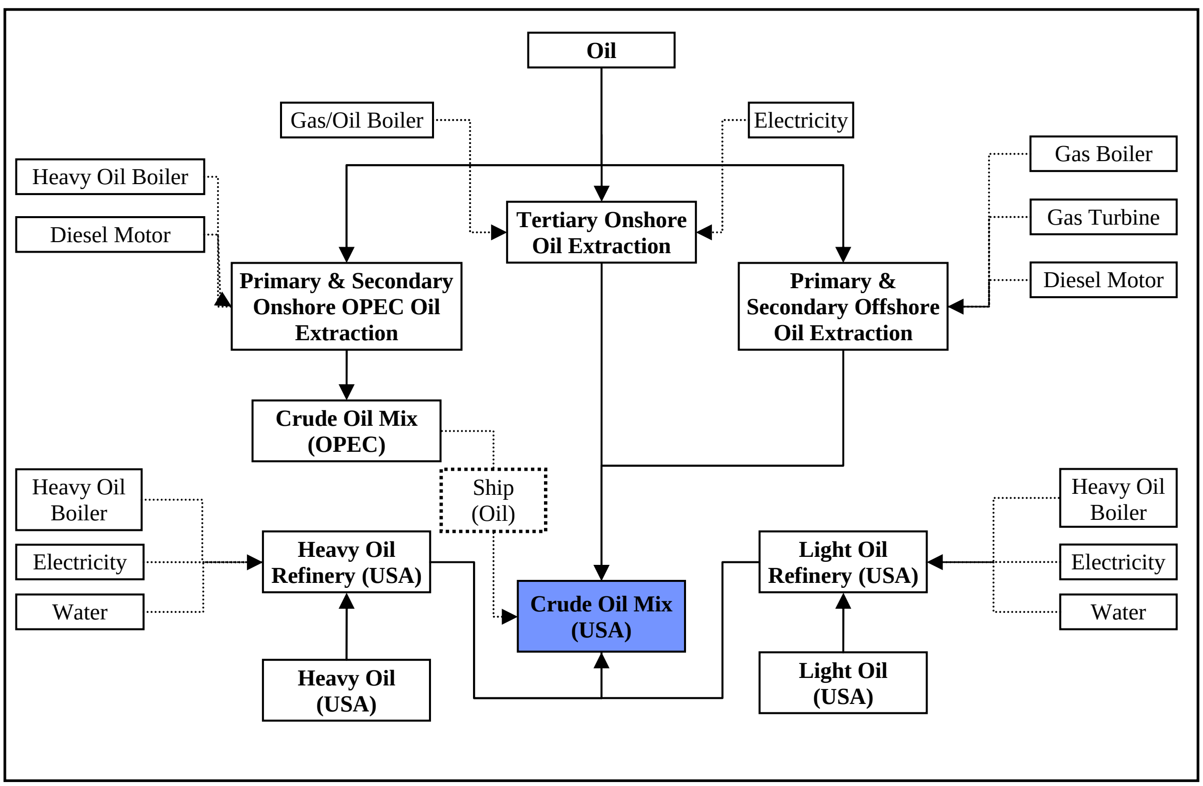



**Figure 3-6: Life cycle stages for oil production.**

**Table 3-6: LCI emission factors inputs for average electric generation.**

| Power Plant | Life Cycle Stage | Emission Factor based on Fuel Input (lb/MMBTU) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $SO_2$ | $NO_x$ as $NO_2$ | CO | $CO_2$ | NMVOC | $CH_4$ | HCl | $N_2O$ |
| Coal-fired ST Power Plant | Coal-fired ST Power Plant | 2.54E-01 | 6.19E-01 | 9.08-02 | 2.26E+02 | 4.54E-02 | 4.54E-03 | 1.31E-02 | 1.30E-02 |
| | Coal Extraction | - | - | - | - | - | 6.746E-1 | - | - |
| | Diesel Motor | 2.73E-01 | 2.25E+00 | 4.88E-01 | 1.73E+2 | 7.13E-03 | 7.13E-03 | - | 7.13E-03 |
| | Explosives (ANFO-Blasting) (kg/kg) | 1.60E-04 | 1.00E-02 | 2.5E-02 | 1.19E-01 | - | - | - | - |
| | Natural Gas-fired GT Power Plant | 9.95E-04 | 9.77E-01 | 1.95E-01 | 1.28E+02 | 9.77E-02 | 1.95E-02 | - | 5.86E-03 |
| Oil-fired ST Power Plant | Oil-fired ST Power Plant | 3.44E-01 | 3.36E-01 | 8.05E-02 | 1.82E+02 | 7.75E-03 | 7.75E-03 | - | 7.40E-03 |
| | Refinery for Oil | - | - | - | - | 2.326E-02 | 2.33E-03 | - | - |
| | Geothermal ST Power Plant | 1.745E+00 | - | - | 7.91E+01 | - | - | - | - |
| | Waste Incineration Plant | 2.27E-01 | 3.43E-01 | 1.37E-01 | 1.20E+02 | 1.37E-01 | 6.85E-03 | 8.48E-02 | 3.43E-03 |

Coal-fired ST power plant included emission control technologies reducing 85% of NOx through combustion modification and flue gas desulphurization (FGD) with spray-dryer absorption (SDA)-reducing 85% $SO_2$, 85% HCl, 90% HF, 85% $H_2S$, and 85% $NH_3$. Flue gas: 6% by volume $O_2$ and stack height is 250 meters.
Oil -fired ST power plant included emission control technologies reducing 50% of NOx and FGD with SDA. Flue gas: 3% by volume $O_2$ and stack height is 200 meters.
Gas turbine power plant included emission control technologies reducing 50% of $NO_x$ and FGD with SDA. Flue gas: 15% by volume $O_2$ and stack height is 10 meters.

### 3.3.3 Natural Gas Combined Cycle (NGCC)

A 500-MW natural gas-fired combined-cycle power plant (NGCC) with 49% electric conversion efficiency based on fuel input is modeled to represent most efficient available central power generation technology. Specifications and assumptions are acquired from a life cycle assessment study of a natural gas combined cycle power generation system (Spath and Mann, 2000). The plant configuration consists of two gas turbines, a three pressure heat recovery steam generator, and a condensing reheat steam turbine. Natural gas is fed into a gas turbine which drives the generator. Waste heat from the turbine is captured by the heat recovery steam generator which provides steam for the steam turbine which in turn also drives a generator. In such a system, usually two thirds of the electric power is provided by the gas turbine and one third by the steam turbine (Hay, 1998).

I. *Manufacturing*: The 500-MW NGCC process is modeled with a lifetime of 30 years operating 8760 hours/year. The auxiliary construction materials used for the process, based on Spath and Mann report (2000), are as follows: concrete: 9.7749E+04 kg/MW, steel: 3.1030E+04 kg/MW, iron: 4.08E+02 kg/MW, aluminum: 2.04E+02 kg/MW.

II. *Operation*: Emission factors used in creating the LCI of the NGCC process are obtained from EPA AP-42 documentation (EPA, 1995). The flue gas has 15% oxygen and the stack height is 150-m. Table 3-7 shows the emission factors of the NGCC process.

**Table 3-7: LCI emission factors inputs for NGCC.**

| **Emission Factor based on Fuel Input (lb/MMBTU) (LHV)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **$SO_2$** | **$NO_x$ as $NO_2$** | **CO** | **$CO_2$** | **NMVOC** | **$CH_4$** | **HCl** | **$N_2O$** |
| 9.95E-04 | 1.44E-01 | 3.33E-02 | 1.22E+02 | 9.88E-03 | 9.55E-03 | - | 3.34E-03 |

### 3.3.4 Solid Oxide Fuel Cell (SOFC) Cogeneration System

An atmospheric pressure simple cycle combined heat and power (CHP) or cogeneration SOFC system is modeled in this study, which represents an emerging technology in CHP applications. Fuel cells range in size between 200kW-250kW; their advantages are their low emissions, low noise, modular design, and high efficiency over load range. Their disadvantages are their high costs and that the fuel require processing unless pure hydrogen is used (EPA, 2002). The main characteristics of the SOFC model are based on the Siemens Westinghouse design (Siemens, 2005). The natural gas fuelled cogeneration tubular SOFC system has an electric output of 125 kW and the exhaust heat can be recovered for hot water and heating loads. The manufacturing process is complicated, and because it is a new technology few details are given in literature.

Details of the manufacturing process, materials, energy requirements and emissions are based on a report done on the LCA of the SOFC by Imperial College of Science (Karakoussis *et al.*, 2000). The LCI consists of the natural gas reformation process, the SOFC main cell and balance of plant manufacturing processes, and the use or operation phase of the SOFC.

I. *Reformation Process*: In the external steam reforming process, natural gas is converted into a gas containing hydrogen, carbon monoxide, with little amounts of water and carbon dioxide. Hydrogen and carbon monoxide obtained from the reforming process is directly used to fuel the SOFC. The modeled reforming process has a conversion efficiency of 80% of fuel input. The reformation process size is 100E+03 kW, operating 8760 hours/year with a lifetime of 20 years. The input to the process is natural gas from pipeline and the output from the process consists of a direct emission from the reforming process of 2.843E+02 lb/MMBTU of $CO_2$.

II. *Manufacturing*: The manufacturing process consists of two main parts: manufacturing of the main cell and manufacturing of the balance of plant.

   (a) Manufacturing of the main cell includes the manufacturing of the two electrodes (anode and cathode), the electrolyte and the interconnect for the SOFC. The cell is built onto a porous cathode support of 1-2 cm in diameter made of LSM fabricated by extrusion. By subsequent layers the cathode (LSM), electrolyte (USZ) and anode layer Ni-YSZ are deposited by thermal spraying and chemical vapor deposition (CVD)/electrochemical vapor deposition (EVD), respectively. The thickness of the cathode, electrolyte and anode layers are around 2-mm, 40-µm and 100-µm, respectively. Cells with a length of 150-cm with an electrochemically active cell area of 1036 $cm^2$ can be mass produced. In the cell concept, the air is supplied from the inner side of the tube while the fuel chamber surrounds the tubular cell. The cells are connected in series by using a ceramic $LaCrO_3$-interconnection, and in parallel by using Ni-felts. The cells are arranged in bundles where a bundle is divided into two compartments: one surrounding the electrochemically active cell area, while in a separate zone the combustion of fuel and air takes place. Sealing is only required in the colder areas. The power density achieved is around 0.2-$Wcm^{-2}$ at a fuel utilization of ~90% and operating temperature of 1000°C under atmospheric pressure (Holtappels and Stimming, 2003). Table 3-8 shows the description of the manufacturing processes of the main cell components (Karakoussis *et* *al*., 2000). Table 3-9 shows the material and process energy requirements of the main cell components used to create the LCA models for each component (Karakoussis *et al.*, 2000).

(b) Manufacturing of the balance of plant (BOP) components includes the manufacturing of the process vessel, stack reformer boards, air delivery system, the exhaust gas and heat management system, and the power management and control system. Table 3-10 shows a description of the BOP components (Karakoussis *et al.*, 2000). Table 3-11 gives the material and process energy requirements of the BOP components which are used in constructing the LCA model for each component.

The electric energy used in the manufacturing processes is obtained from USA average electric generation mix and the heat used in the manufacturing processes is obtained from gas boilers.

III. *Operation*: Operating system performance estimates are based on the CHP125 Siemens Westinghouse SOFC module (Siemens, 2005). Table 3-12 shows the operating characteristics estimated from the system performance graph (Appendix A), which is used in creating seven LCA models of the SOFC for the indicated electric output levels.

**Table 3-8: SOFC manufacturing processes for the main cell (Karakoussis *et al.*, 2000).**

| Manufacturing Process of the Main Cell | Description |
|---|---|
| Cathode paste preparation | Doped $LaMnO_3$ powder is mixed with auxiliary materials and water in a Z blade mixture to form the cathode paste. |
| Cathode extrusion | The paste is first extruded into a hemispherical mold to form the closed end of the tube. Then the mold is removed and the extrusion continuous in a smooth fashion allowing for the formation of the remaining cylindrical section. |
| Cathode Sintering | The extruded tube section is then sintered at approximately 1500°C to form the tubular building block. |
| Deposit interconnect | Doped $LaCrO_3$ powder is fed to a plasma spray gun and sprayed onto the cathode tube. |
| Mask | A mask is applied on the interconnect. |
| Fire | A low temperature continuous furnace is used. |
| Deposit electrolyte | A film of YZ oxide is applied on the cathode tube using the electrochemical vapor deposition process. The materials used to form the film are $ZrCl_4$ and $YCl_3$. |
| De-Mask | The mask is removed. |
| Ni plating | The interconnect is electroplated with Ni to provide electrical connection between tubes. |
| Re-mask for anode deposition | A mask is applied on the interconnect. |
| Anode Slurry preparation | A mixture of Ni-$ZrO_2(Y_2O_3)$ powders is mixed with auxiliary materials to produce a highly viscous slurry. |
| Anode slurry dipping | The tubes are dipped into the slurry containers and then extracted at a slow rate to ensure uniform thickness of the anode film. |
| Anode sintering | The tubes are then sintered at 1300°C in a high temperature continuous furnace. |

**Table 3-9: Material and energy for the SOFC main cell (Karakoussis *et al.*, 2000).**

| Component of Main Cell | Material (kg/kW) | Energy for the Production of Materials (MJ/kW) | Manufacturing Process | Manufacturing Process Energy (MJ/kW) |
|---|---|---|---|---|
| Dopped $LaMnO_3$ | 4.257 | 221.73 | Cathode Paste Preparation | 0.36 |
| Water | 0.983 | 0.0197 | Cathode Extrusion | 0.82 |
| Doped $LaCrO_3$ | 0.062 | 3.21 | Deposit Interconnect (Atmospheric Plasma Spray) | 207.36 |
| Ni Oxide | 0.078 | 0.504 | Mask | 0.6 |
| | | | Fire in Continuous Furnace | 0.61 |
| Ni | 4.17E-05 | 0.025 | Nickel Platting | 0.12 |
| $ZrCl_4$ | 0.828 | 28.76 | De-masking | 1.83 |
| $YCl_3$ | 0.122 | 4.23 | Re-masking for anode | 0.06 |
| $ZrO_2(Y_2O_3)$ | 0.078 | 2.7 | Deposit Electrolyte (EVD) | 46.29 |
| Polyvinyl butyral (PVB) | 0.031 | 1.566 | Anode Slurry Preparation | 0.24 |
| Ethanol | 0.187 | 9.618 | Anode Slurry Dipping | 0.12 |
| Polyethylene glycol | 0.012 | 0.711 | Anode Sintering | 8.15 |
| Dibutyl Phthalate | 0.012 | 1.55 | | |
| | | | Cathode Sintering | 8.15 |

**Table 3-10: SOFC BOP components (Karakoussis *et al.*, 2000).**

| Component of BOP | Description |
|---|---|
| Process Vessel | Steel vessel containing the system. |
| Pressure vessel insulation | Micropours Alumina-Silica material used for insulation. This type of insulation is commonly used in industry. |
| Piping for air and fuel supply systems | This includes all pipe-work, valves, blowers, compressors etc. for providing continuous supplies of the fuel gas and air to the SOFC stack |
| Air plenum assemblies | Components made of Alumina provide air to the SOFC tubes |
| Stack reformer boards | Pre reforming of the fuel is taking place on these boards made of Nickel .The main reforming is internal. |
| Desulphrizer | In this component potentially deleterious sulphur compounds are removed from the hydrocarbon fuel. |
| Air pre heater | This component issued to provide the necessary heat for start up. |
| Heat exchangers | The heat is generated during the operation of the system is utilized by the heat management system composed of a number of heat exchangers. |
| Power conditioning system | The AC current produced by the fuel cell system is converted to DC. |

**Table 3-11: Material and energy for SOFC BOP (Karakoussis *et al.*, 2000).**

| Component of BOP | Materials (kg/kW) | Energy for Material Production (MJ/kW) | Manufacturing Process Energy (MJ/kW) |
|---|---|---|---|
| Pressure Vessel | Steel… 50 | 1120 | 56 |
| Pressure Vessel Insulation | Alumina Silica…. 0.5 | 10 | 0.5 |
| Piping | Steel… 5 | 112 | 5.6 |
| Air Plenum Assemblies | Aluminum… 4.2 | 72.91 | 3.64 |
| Stack Reformer Boards | Ni… 0.2 | 58.28 | 2.91 |
| De-sulphurizer | Steel… 0.05 | 1.12 | 0.08 |
| | Zn… 0.01 | 0.499 | |
| Air Pre-heater | Steel… 2 | 44.8 | 2.24 |
| Heat Exchangers | Incaloy.. 2 | 49.28 | 4.704 |
| | Steel… 2 | 44.8 | |
| Power Conditioning System | Aluminum… 0.3 | 84.52 | 4.33 |
| | Purified Silica… 0.004 | 0.556 | |
| | Cu… 0.02 | 1.2 | |
| | Plastics… 0.006 | 0.375 | |
| Other | | | 160.03 |

**Table 3-12: SOFC estimated operating performance (Siemens, 2005).**

| Percent Load | Current (Amps) | Net Electric Output (kWe) | Heat Recovery ($kW_t$) | Electric Efficiency (%) | Thermal Efficiency (%) | Overall Efficiency (%) | Power to Heat Ratio |
|---|---|---|---|---|---|---|---|
| 62% | 300 | 78 | 32 | 51 | 21 | 72 | 2.43 |
| 68% | 350 | 85 | 45 | 50 | 24 | 74 | 2.08 |
| 78% | 400 | 98 | 55 | 50 | 28 | 78 | 1.79 |
| 85% | 450 | 106 | 65 | 49 | 30 | 79 | 1.63 |
| 93% | 500 | 116 | 80 | 48 | 32 | 80 | 1.5 |
| 100% | 550 | 125 | 95 | 45 | 35 | 80 | 1.29 |
| 104% | 600 | 130 | 109 | 44 | 37 | 81 | 1.19 |

### 3.3.5 Microturbine (MT) Cogeneration System

Microturbines range in sizes between 30kW-350kW; their advantages are the small number of moving parts, compact size, light weight, low emissions, and that no cooling is required; whereas their disadvantages are their high costs, relatively low mechanical efficiency, and that they are limited to lower temperature cogeneration applications (EPA, 1995). Microturbines are also emerging technologies for cogeneration and CHP applications and can be considered as small gas turbines ranging in size between 30-350 kW. The characteristics of the microturbine system modeled in this study are based on the microturbine tested for CHP system by the Greenhouse Gas Technology Center (GHG Center) under the Environmental Technology Verification Program (ETV) (USEPA-GHG, 2003). The main components are a Capstone 60 MicroTurbineTM and a heat exchanger. Electric power is generated by a Capstone 60 microturbine with a nominal power output of 60 kW (59 °F, sea level).

The system operates on natural gas and consists of an air compressor, recuperator, combustor, turbine, and a permanent magnet generator. Preheated air is mixed with fuel, and this compressed fuel/air mixture is burned in the combustor under constant pressure conditions. The resulting hot gas is allowed to expand through the turbine section to perform work, rotating the turbine blades to turn a generator which produces electricity. The rotating components are mounted on a single shaft supported by patented air bearings that rotate at over 96,000 revolutions per minute (rpm) at full load. The exhaust gas exits the turbine and enters the recuperator that pre-heats the air entering the combustor to improve the efficiency of the system. The exhaust gas is then directed to the heat-recovery unit. The LCI inventory consists of inputs to the MT process including natural gas from the gas pipeline and auxiliary materials used in the construction of the unit process, operation phase of the MT cogeneration system and outputs (air emissions) from the unit processes.

I. *Manufacturing*: the manufacturing process is simplified to only include the material requirement for the manufacturing of MT (cooling systems, water losses and other processes involved with the manufacturing process of the MT are ignored). The material requirement for construction of the MT cogeneration unit process is 1.26333E+04 kg/MW of steel based on the weight of a MT unit (758 kg) given in literature (USEPA-GHG, 2003).

II. *Operation*: Table 3-13 shows the MT system operating characteristics at maximized heat recovery (USEPA-GHG, 2003), which is used in creating the four LCA MT unit processes for the indicated part load operation characteristics. Table 3-14 shows the emissions factors of LCI of MT cogeneration unit process corresponding to the specified part loads.

Table 3-13: MT operating characteristics at maximized heat recovery (USEPA-GHG, 2003).

| Percent Load (%) | Heat Recovery ($10^3$ BTU/hr) | Thermal Efficiency (%) | Net Electric Efficiency (%) | Net Power Delivered (kWe) | Total Efficiency (%) |
|---|---|---|---|---|---|
| 100 | 373 | 52 | 26 | 54.9 | 78 |
| 75 | 317 | 56 | 24 | 39.9 | 81 |
| 50 | 239.6 | 57 | 20 | 24.8 | 77 |
| 25 | 148.5 | 58 | 13 | 9.8 | 71 |

Table 3-14: LCI emission factors inputs for MT cogeneration system (USEPA-GHG, 2003).

| MT Part Load | Unit | NOx | CO | THC | $CH_4$ | $CO_2$ | NMVOC |
|---|---|---|---|---|---|---|---|
| 100 % | ppmvd at 15% $O_2$ | 3.13E+00 | 3.53 E+00 | 1.06 E+00 | <0.9 E+00 | | |
| 75% | | 3.30 E+00 | 1.54 E+02 | 7.03 E+01 | 4.35 E+01 | | |
| 50% | | 4.26 E+00 | 5.82 E+02 | 1.19 E+02 | 7.21 E+02 | | |
| 25% | | 6.56 E+00 | 3.38 E+02 | 3.27 E+02 | 1.98 E+02 | | |
| 100 % | lb/kWhe | 1.49E-04 | 1.03E-04 | 1.77E-05 | 1.58E-05 | 1.54E+00 | |
| 75% | | 1.71E-04 | 4.86E-03 | 1.27E-03 | 7.84E-04 | 1.61E+00 | |
| 50% | | 2.67E-04 | 2.26E-02 | 2.61E-02 | 1.57E-02 | 1.87E+00 | |
| 25% | | 6.31E-04 | 1.98E-02 | 1.09E-02 | 6.65E-03 | 2.89E+00 | |
| 100 % | lb/MBTU | 4.36E-02 | 3.02E-02 | 5.18E-03 | 4.63E-03 | 4.51E+02 | 5.57E-04 |
| 75% | | 5.01E-02 | 1.42E+00 | 3.72E-01 | 2.30E-01 | 4.72E+02 | 1.42E-01 |
| 50% | | 7.82E-02 | 6.62E+00 | 7.64E+00 | 4.60E+00 | 5.48E+02 | 3.05E+00 |
| 25% | | 1.85E-01 | 5.80E+00 | 3.19E+00 | 1.95E+00 | 8.47E+02 | 1.24E+00 |

Emission factors reported are based on fuel output (LHV), to obtain emission factors based on fuel input divide by the conversion efficiency at the specific percent load.
NMVOC=THC-CH4

### 3.3.6 Internal Combustion Engine (ICE) Cogeneration System

Spark ignited reciprocating engines or internal combustion engines (ICE) are usually less than 5MW; their advantages are their high power efficiency with part load flexibility, fast start-up, relatively low investment cost, good load following capability, and low-pressure gas operation. Their disadvantages are their high maintenance costs, lower temperature cogeneration application limitations, relatively high air emissions, high level of frequency noise, and that they must be cooled even if recovered heat is not used (EPA, 2002). There are different types of ICEs depending on size, type of ignition and speed. Natural gas-fired ICEs are spark ignition engines (versus diesel compression ignition engines). In this study, the ICE cogeneration system modeled is a 150 kW engine and specifications of the engine are based on commercially available engines (Caterpillar-Inc., 1999).

The ICE requires fuel, air, compression, and a combustion source to function. The four-stroke, spark-ignited natural gas reciprocating engine has an intake, compression, power and exhaust cycle. In the intake phase, as the piston starts in the bottom dead center position in the cylinder and the intake valve opens, the cylinder fills with fuel and air moving the piston to top dead center. The piston is then returned to the bottom of the cylinder during the compression process, at which point the spark plug emits a spark to ignite the fuel/air mixture. This controlled reaction, or "burn," forces the piston upward thereby turning the crank shaft and producing power. In the exhaust phase, the piston moves back down to its original position and the spent mixture is expelled through the open exhaust valve. Energy in the fuel is released during combustion and is converted to shaft work and heat. Shaft work drives the generator while heat is liberated from the engine through coolant, exhaust gas and surface radiation (ONSITE-SYCOM, 1999).

Approximately 60-70% of the total energy input is converted to heat, some of which can be recovered from the engine exhaust and jacket coolant, while smaller amounts are also available from the lube oil cooler and the turbocharger's intercooler and after-cooler. Steam or hot water can be generated from recovered heat that is typically used for space heating, reheat, domestic hot water and absorption cooling. Natural gas reciprocating engines are a popular choice for commercial CHP due to good part-load operation, ability to obtain an air quality permit and availability of size ranges that match the load of many commercial and institutional end-users. Reciprocating engines exhibit high electric efficiencies, meaning that there is less available rejected heat. This is often compatible with the thermal requirements of the end-user (ONSITE SYCOM, 1999).

I. *Manufacturing*: The 150 kW ICE modeled has a lifetime of 5.1 years and operating 8760 hours/year. The manufacturing process that is modeled is simplified to only include the construction material required for manufacturing the ICE. The construction material used in the process is steel: 2.72722E+04 kg/MW.

II. *Operation*: specifications for the 150 kW ICE process is given in Table 3-15 including part load operation characteristics. Emission factors used in the LCI for the process are given in

Table 3-16 based on reported data for this specific engine (Caterpillar-Inc., 1999) except for $CO_2$ and $SO_2$ emission factors which are based on EPA-AP 42 estimates (EPA, 1995). Emission factors given in Table 3-16 are uncontrolled values. Emission factors for a typical ICE operation using EPA-AP 42 data (EPA, 1995) are given in Table 3-17.

III. *Emissions control*: A three way catalytic converter is modeled to reduce the emissions resulting from the ICE. The three way catalytic converter reduces $NO_x$ emissions by 90%, CO by 50%, and NMVOC by 50%.

**Table 3-15: ICE operation characteristics (Caterpillar-Inc. 1999).**

| | **Percent Load** | | |
|---|---|---|---|
| **ICE 150 kW** | **100%** | **75%** | **50%** |
| Engine Power | 172 | 129 | 87 |
| Engine Efficiency (%) | 33.4 | 30.4 | 26.6 |
| Thermal Efficiency (%) | 54.8 | 57.8 | 60.8 |
| Total Efficiency (%) | 88.3 | 88.2 | 87.4 |
| Power to Heat Ratio | 0.609 | 0.526 | 0.438 |
| Max Power Output | 172 | 145 | 97 |
| Min Power Output | 151 | 113 | 76 |

**Table 3-16: LCI emission factors inputs for ICE based on commercial data (Caterpillar-Inc., 1999).**

| | **Uncontrolled Emissions Factor (lb/MBTU) based on fuel input (LHV)** | | | **Uncontrolled Emissions Factor (lb/MBTU) based on fuel output** | | |
|---|---|---|---|---|---|---|
| | 100% Load | 75% Load | 50% Load | 100% Load | 75% Load | 50% Load |
| $SO_2$[a] | 5.88E-04 | 5.88E-04 | 5.88E-04 | 1.76E-03 | 1.93E-03 | 2.21E-03 |
| $NO_x$ (as $NO_2$) | 6.24E+00 | 5.93E+00 | 5.19E+00 | 1.87E+01 | 1.95E+01 | 1.95 E+01 |
| CO | 4.68E-01 | 4.26E-01 | 3.99E-01 | 1.4 E+00 | 1.4 E+00 | 1.5 E+00 |
| THC | 8.02E-01 | 7.68E-01 | 8.68E-01 | 2.4 E+00 | 2.3 E+00 | 2.6 E+00 |
| NMVOC[a] | 1.34E-01 | 1.25E-01 | 1.07E-01 | 4.0E-01 | 4.0 E-01 | 4.0 E-01 |
| $CH_4$ | 7.01E-01 | 6.41E-01 | 5.86E-01 | 2.1 E+00 | 2.1 E+00 | 2.2 E+00 |
| $CO_2$[b] | 1.10E+02 | 1.10E+02 | 1.10E+02 | 3.30E+02 | 3.62E+02 | 4.14E+02 |

[a] $SO_2$ emission factors are based on EPA AP 42 uncontrolled emission factors for ICE based on 100% conversion of fuel sulfur to $SO_2$.
NMVOC is not reported (CAT) but estimated by subtracting THC from methane emission factors.
[b] $CO_2$ emission factors are based on EPA AP-42 values.

**Table 3-17: LCI emission factors inputs for ICE based on EPA data (EPA, 1995).**

| **EPA ICE** | **Uncontrolled Emissions Factor (lb/MBTU) of fuel input (LHV)** | |
|---|---|---|
| | 90-105% Load | <90% Load |
| $NO_x$ (as $NO_2$) | 2.21E+00 | 2.27E+00 |
| CO | 3.72E+00 | 3.51E+00 |
| THC[a] | 3.58E-01 | 3.58E-01 |
| NMVOC[b] | 2.96E-02 | 2.96E-02 |
| $CH_4$[c] | 2.30E-01 | 2.30E-01 |
| $CO_2$ | 1.10E+02 | 1.10E+02 |

[a] Emissions for THC is based on measured emission levels from 6 source tests.
[b] NMVOC emission factors used in the model are based on VOC emission factor reported in the EPA AP-42, which is the sum of the emission factors for all speciated organic compounds except methane and ethane.
[c] Methane emission factors in the EPA AP-42 report is determined by subtracting the NMVOC and ethane emission factors from THC (or TOC) emission factors.

### 3.3.7 Gas boiler

A 1-MW gas boiler with a thermal efficiency of 88.7% of fuel input is modeled. The emissions from the boiler are acquired from EPA's AP-42.

The main emissions from natural gas-fired boilers include $NO_x$, CO, $CO_2$, $CH_4$, $N_2O$, VOC, trace amounts of $SO_2$, and PM (EPA AP-42, 1999). The principal mechanism of $NO_x$ formation in natural gas combustion is thermal $NO_x$ which occurs through the thermal dissociation and subsequent reaction of $N_2$ and $O_2$ molecules in the combustion air. The formation of thermal $NO_x$ is affected by: oxygen concentration, peak temperature, and time of exposure to peak temperature as well as flame configuration (these factors affect $NO_x$ emission levels). The rate of CO emissions from boilers depends on the efficiency of natural gas combustion. In some cases, the addition of $NO_x$ control systems may reduce combustion efficiency, resulting in higher CO emissions relative to uncontrolled boilers. The rate of VOC emissions from boilers also depends on combustion efficiency. VOC emissions are minimized by high combustion temperatures, long residence times at those temperatures, and turbulent mixing of fuel and combustion air. $SO_2$ emissions from natural gas-fired boilers are low because the pipeline quality of natural gas has very low levels of sulfur. Unprocessed natural gas has higher $SO_2$ emissions due to higher sulfur levels in the natural gas. Also, sulfur containing odorants (added to natural gas for detecting leaks) leads to small amounts of $SO_2$ emissions from the boiler (EPA AP-42, 1999).

Greenhouse gas ($CO_2$, $CH_4$, and $N_2O$) emissions are all produced during natural gas combustion. Nearly all of the fuel carbon is converted to $CO_2$ during the combustion process, which is independent of boiler type. Fuel carbon not converted to $CO_2$ results in $CH_4$, CO, and/or VOC emissions, which is due to incomplete combustion and are insignificant compared to $CO_2$ levels. $N_2O$ emissions are minimized with high combustion temperatures and low excess oxygen levels (<1%); methane emissions are minimized in similar conditions. Particulate matter emission (less than one micrometer in size) from natural gas combustion is low because natural gas is a gaseous fuel (EPA, 1995).

I. *Manufacturing*: the modeled 1 MW gas boiler has a lifetime of 20 years operating 4000 hours/year. The construction material used in the process is 1.00E+04 kg/MW of steel.

II. *Operation*: The 1 MW gas boiler has a 88.7% thermal conversion efficiency based on fuel input. The flue gas has 3% $O_2$ content by volume and the stack height is 10 meters. Table 3-18 shows the emission factors used in the LCI of the process.

**Table 3-18: LCI emission factors inputs for gas boiler (EPA, 1995).**

| **Emission Factor based on Fuel Input (lb/MMBTU) (LHV)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **$SO_2$** | **$NO_x$ as $NO_2$** | **CO** | **$CO_2$** | **NMVOC** | **$CH_4$** | **HCl** | **$N_2O$** |
| 5.88E-04 | 4.92E-02 | 8.24E-02 | 1.28E+02 | 1.17E-02 | 2.25E-03 | - | 6.27E-04 |

## 3.4 LIFE CYCLE IMPACT ASSESSMENT

The impact assessment step of the LCA is intended to evaluate the magnitude and significances of potential environmental impacts of the product systems using the results of the life cycle inventory analysis (ANS/ISO, 1997). The elements included in the life cycle impact assessment step in this study are: (a) category definition, which provides a definition of the impact categories considered (b) classification, which aims to assign inventory input and output data to categories and (c) characterization, which is a quantitative step used to model categories in terms of indicators and provides the basis of aggregation of the inventory input and output within the category; this is done in terms of the indicator to represent an overall change to the impact category (ANS/ISO, 1997). For some of the environmental impact categories, there is consensus about equivalency factors to be used in the estimation of the total impact, such as global warming potential, tropospheric ozone precursors potential, and acidification potentials.

The environmental impact indicators considered in the LCA to quantify the potential contribution of the product's inventory flow are:

- Primary Energy Consumption (PE),
- Global Warming Potential (GWP),
- Acidification Potential (AP), and
- Tropospheric Ozone Precursors Potential (TOPP).

### 3.4.1 Primary Energy Consumption

I. *Category definition*: Primary energy resource depletion is a category that can be used to assess the impact of resource extraction on the availability of natural resources. It can represent global, continental, regional, and/or local impact.

II. *Classification and characterization*: Primary energy consumption is a quantitative indicator that measures the total amount (sum) of primary energy resources needed to deliver energy. It quantifies resource depletion. Resources are products that can be converted to energy carriers including nonrenewable resources, e.g. oil and coal from which fuels can be derived, as well as renewable resources, e.g. wind, hydro-power etc. This impact addresses only the depletion effect of resource extraction, i.e. the upper end of the process chains, and not impacts resulting from extraction processes, such as emissions. The impact of primary energy use determines the availability of natural resources, which translates to issues such as efficiency, conservation, sustainable use, etc.

The elements in the LCI that are considered in the PEC impact category are fossil and non-renewable energy carriers for non-renewable resources, and biomass, geothermal, hydro, solar and wind for the renewable resources. Wastes are also considered in PE as secondary resources because of their potential to be re-used.

### 3.4.2 Global Warming Potential

I. *Category definition*: Global warming or the greenhouse effect is a category that is used to describe the effect of increasing temperature in the lower atmosphere. Global warming represents a global impact. The natural greenhouse effect occurs when greenhouse gases trap heat within the surface-troposphere system, as they absorb infrared radiation emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds, where atmospheric radiation occurs at all sides including downward to the Earth's surface. Atmospheric radiation is strongly coupled to the temperature of the level at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, -19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C (IPCC, 2001).

An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore an effective radiation into space from a higher altitude at lower temperature. This occurrence causes radiative forcing, an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system. This is the *enhanced greenhouse effect* (IPCC, 2001).

II. *Classification and Characterization*: According to IPCC (2001), *Global Warming Potential* (GWP) is an index describing the radiative characteristics of well mixed greenhouse gases, which represents that combined effect of the differing times these gases remain in the atmosphere and their radiative effectiveness in absorbing outgoing infrared radiation. This index approximates that time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere relative to that of carbon dioxide.

Since different greenhouse gases have different residence time in the atmosphere, the GWPs of substances are based on modeling and are quantified for time horizons. A time horizon of 100 years is used in this study (IPCC, 1996). To calculate the $CO_2$ equivalents of greenhouse gases, mass-based relative global warming potentials are used which specify for each greenhouse gas the equivalent amount of $CO_2$ having the same radiative forcing in the 100 year time-horizon. The major greenhouse gases from the LCI used in the GWP impact category are: $CO_2$, $CH_4$ and $N_2O$; other greenhouse gases considered in the GWP impact category are hydrofluorocarbons and fully fluorinated species. Table 3-19 shows the carbon dioxide equivalents of the major greenhouse gases.

The GWP equivalence of the greenhouse gases included in the study are calculated according to equation [3-1]:

$$GWP_{equivalence} = \sum \left( e_i \times GWP_i \right) \qquad [3\text{-}1]$$

where,

$e_i$ = mass of greenhouse (i) in kg, and

$GWP_i$ = global warming potential of emission (i), in [kg/kg]

**Table 3-19: GWP equivalent factors (IPCC, 1996).**

| Emission Equivalents | $CO_2$ | $CH_4$ | $N_2O$ | Perfluoromethane | Perfluoroethane |
|---|---|---|---|---|---|
| **$CO_2$ equivalents** | 1 | 21 | 316 | 6500 | 9200 |

### 3.4.3 Acidification Potential

I. *Category definition*: Acidification is a category that represents a local as well as regional impact. Acidification is caused by releases of protons in the terrestrial or aquatic ecosystems. In the terrestrial ecosystem, the effects are seen in softwood forests (e.g. spruce) as inefficient growth and, as a final consequence, dieback of the forests. In the aquatic ecosystem, the effects are seen as acid lakes without wildlife. Buildings, constructions, sculptures and other objects worthy of preservation are also damaged by acid rain (EEA, 1997).

Acid air emissions, such as $SO_2$ and $NO_x$, deposited in solution form are referred to as acid precipitation and deposition in dry gas and compounds as dry deposition. $SO_2$ contributes more to the acidity of precipitation than does $CO_2$ present at higher levels in the atmosphere mainly because it is significantly more soluble in water than $CO_2$. Although acid rain can originate from the direct emission of strong acids, most of it is a secondary air pollutant produced by the atmospheric oxidation of acid-forming gases. Such chemical reactions play a dominant role in determining the nature, transport, and fate of acid precipitation. Acid rain spreads out over several hundred to several thousand kilometers; this classifies it as a *regional* air pollution problem compared to *local* air pollution problem such as smog, or a *global* one, such as greenhouse gases. Emissions from industrial operations and fossil fuel combustion are the major sources of acid-forming gases (Manahan, 1994).

II. *Classification and characterization*: Acidification potential (AP) is the result of aggregating acid air emissions, expressed in $SO_2$ equivalents. The $SO_2$ equivalents express the acidification potential (AP) and are calculated from the molecular weights and the proton binding potential of the respective emissions (by definition AP is equal to one for $SO_2$).

Substances from the LCI that are considered for the AP impact category are: $NO_x$, HF, HCl, $H_2S$, and $NH_3$. Table 3-20 shows the AP equivalents of the substances considered in the AP impact category. $AP_{eq}$ is calculated as indicated in equation [3-2].

$$AP_{equivalence} = \sum \left( e_i \times AP_i \right) \qquad [3\text{-}2]$$

where,

$e_i$ = mass of emission (i) in kg, and

$AP_i$ = acidification potential of emission (i), in [kg/kg]

**Table 3-20: AP equivalent factors (EEA, 2000).**

| Emission Equivalents | NOx | $SO_2$ | HCL | HF | $H_2S$ | $NH_3$ |
|---|---|---|---|---|---|---|
| **$SO_2$ equivalents** | 0.696 | 1.0 | 0.878 | 1.601 | 0.983 | 3.762 |

### 3.4.4 Tropospheric Ozone Potential Precursor

I. *Category definition*: Tropospheric ozone formation is a category that evaluates the photochemical ozone formation (smog) caused by the degradation of organic compounds (VOC) in the presence of light and nitrogen oxides ($NO_x$). Tropospheric ozone formation represents a regional impact.

Photochemical smog is a major air pollution phenomenon that occurs in urban areas where the combination of pollution-forming emissions and appropriate atmospheric conditions are conductive to its formation. In order for high levels of smog to form, relatively stagnant air must be subjected to sunlight under low humidity conditions in the presence of pollutant nitrogen oxides and hydrocarbons. Although not a great threat to the global atmosphere, smog does pose significant hazards to living things and materials in local urban areas. Ozone, which serves an essential protective function in the stratosphere, is the major cause of tropospheric smog. Surface ozone levels are used as a measure of smog. Ozone phototoxicity raises particular concern in respect to trees and crops, and in addition, ozone is responsible for most of the respiratory system distress (breathing is impaired at ozone levels at about 0.1 ppm) and eye irritation resulting from human exposure to smog (Manahan, 1994).

The reaction can be described in a simplified way in terms of four steps (EEA, 1997): (1) reaction between volatile organic compounds (VOC) and hydroxyl radicals (OH) to form organic peroxy radicals; (2) the peroxy radicals react with nitrogen mono-oxide (NO) to form nitrogen dioxide ($NO_2$); (3) $NO_2$ react in the presence of sunlight to form nitrogen monoxide and oxygen atoms; and (4) atomic oxygen reacts with oxygen ($O_2$) to form ozone ($O_3$).

II. *Classification and characterization*: The Tropospheric Ozone Precursor Potential (TOPP) is the mass-based equivalent of the ozone formation rate from precursors, measured in ozone precursor equivalents. The TOPP represents the potential formation of near-ground (tropospheric) ozone which can cause summer photochemical smog.

Substances from the LCI considered for the TOPP impact categories are: $NO_x$, NMVOC, CO, and $CH_4$. Table 3-21 shows the TOPP equivalents of the substances considered in calculating the TOPP impact, based on European Environmental Agency

(2000). The TOPP equivalents which express the ozone formation rate potential (TOPP) is calculated according to equation [3-3].

$$TOPP_{equivalence} = \sum \left( e_i \times TOPP_i \right) \qquad [3\text{-}3]$$

where,

$e_i$ = mass of emission (i) in kg, and

$TOPP_i$ = tropospheric ozone precursor potential of emission (i), in [kg/kg]

**Table 3-21: TOPP equivalent factors (EEA, 2000).**

| **Emission Equivalents** | **$CH_4$** | **$NO_x$** | **NMVOC** | **CO** |
|---|---|---|---|---|
| **TOPP equivalents** | 0.014 | 1.22 | 1.0 | 0.11 |

## 3.5 LIFE CYCLE INTERPRETATION

In the life cycle interpretation phase of the LCA, the findings of the impact assessment are analyzed to identify the significant environmental issues, evaluate the results and to draw conclusions and possibly recommendations from the results.

The environmental impact indicators identified in the life cycle impact assessment step (Section 3.4), PE, GWP, AP, and TOPP, are used in the assessment of the potential environmental impacts resulting from the modeled energy systems when used to produce a unit output of energy, i.e. for the functional unit of 1 kWh. All the environmental factors are calculated based on the LHV of fuel input. Note that for all systems, the functional unit is the production of 1 kWh of electric energy except for the gas boiler where the functional unit is the production of 1 kWh output of thermal energy.

### 3.5.1 Primary Energy Consumption

The LCA results indicate that the total PE consumption factor values increase with decreasing percent load operation (as the power to heat ratio decreases with decreasing part load operation) for both the MT and ICE cogeneration systems: i.e., the MT and ICE systems have the lowest PE consumption factor value at full operating load. For the SOFC, the PE consumption factor value is approximately constant at the modeled part load operations, but unlike the MT and ICE systems, it shows a slight decrease in the total PE consumption factor values with decreasing part load operation due to a slight increase in power to heat ratio with decreasing part load operation. Table 3-22 includes the total PE consumption factors obtained from the energy systems when used to produce a unit output of electrical energy and Figure 3-7 shows an illustration of these values. The SOFC has the lowest PE consumption factor values amongst the cogeneration systems followed by the ICE and finally MT because of the higher power to heat ratio of the SOFC compared to the MT and ICE ratios. Table 3-23 shows the power to heat ratios of the cogeneration systems. The NGCC has the lowest overall PE consumption values, which are comparable with the SOFC factors. The PE consumption value of the average electric grid is 32% higher than that of the NGCC but is comparable to the PE consumption values resulting from the ICE when operated at full load. Table 3-24 shows the PE consumption factor for the gas boiler when used to produce a unit output of thermal energy.

**Table 3-22: LC PE consumption factors resulting from energy systems producing unit power output.**

| System | | PE (kWh/kWh$_e$) | Non-renewable Resources (kWh/kWh$_e$) | Renewable Resources (kWh/kWh$_e$) | Wastes (kWh/kWh$_e$) |
|---|---|---|---|---|---|
| MT | MT 100%Load | 3.99E+00 | 3.98E+00 | 8.44E-04 | 3.31E-03 |
| | MT 75%Load | 4.32E+00 | 4.31E+00 | 9.14E-04 | 3.57E-03 |
| | MT 50%Load | 5.22E+00 | 5.22E+00 | 1.10E-03 | 4.26E-03 |
| | MT 25%Load | 7.97E+00 | 7.96E+00 | 1.68E-03 | 6.39E-03 |
| ICE | ICE 100% Load | 3.13E+00 | 3.13E+00 | 6.73E-04 | 2.85E-03 |
| | ICE 75% Load | 3.44E+00 | 3.43E+00 | 7.38E-04 | 3.09E-03 |
| | ICE 50% Load | 3.93E+00 | 3.92E+00 | 8.31E-04 | 3.25E-03 |
| SOFC | SOFC 104% Load | 3.00E+00 | 2.99E+00 | 1.10E-03 | 5.58E-03 |
| | SOFC 100% Load | 2.93E+00 | 2.92E+00 | 1.09E-03 | 5.53E-03 |
| | SOFC 93% Load | 2.75E+00 | 2.74E+00 | 1.05E-03 | 5.39E-03 |
| | SOFC 85% Load | 2.69E+00 | 2.69E+00 | 1.04E-03 | 5.35E-03 |
| | SOFC 78% Load | 2.64E+00 | 2.63E+00 | 1.03E-03 | 5.30E-03 |
| | SOFC 68% Load | 2.64E+00 | 2.63E+00 | 1.03E-03 | 5.30E-03 |
| | SOFC 62% Load | 2.59E+00 | 2.58E+00 | 1.01E-03 | 5.26E-03 |
| **US Average Electric** | | 3.09E+00 | 2.79E+00 | 9.81E-02 | 1.98E-01 |
| **NGCC** | | 2.27E+00 | 2.27E+00 | 4.80E-04 | 1.85E-03 |

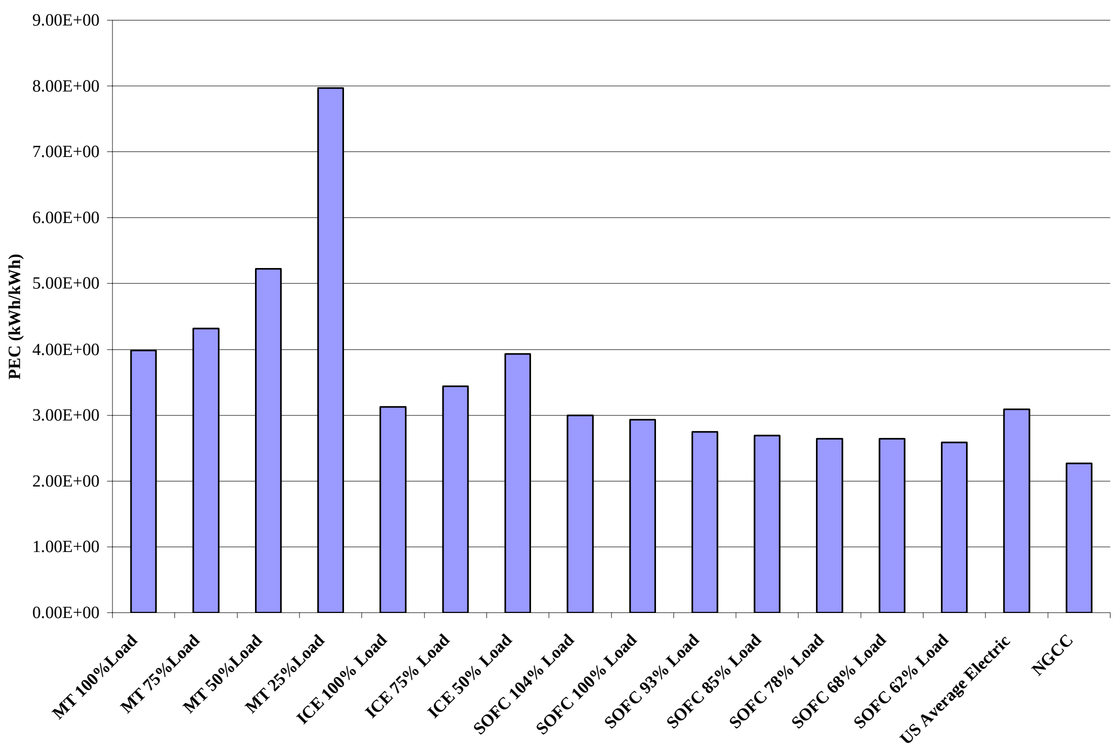



**Figure 3-7: LC PE consumption of energy systems producing unit power output.**

**Table 3-23: Power to heat ratios of cogeneration systems.**

| System | | Power to Heat Ratios |
|---|---|---|
| MT | MT 100%Load | 5.02E-01 |
| | MT 75%Load | 4.29E-01 |
| | MT 50%Load | 3.53E-01 |
| | MT 25%Load | 2.26E-01 |
| ICE | ICE 100% Load | 6.09E-01 |
| | ICE 75% Load | 5.26E-01 |
| | ICE 50% Load | 4.38E-01 |
| SOFC | SOFC 104% Load | 1.19E+00 |
| | SOFC 100% Load | 1.29E+00 |
| | SOFC 93% Load | 1.50E+00 |
| | SOFC 85% Load | 1.63E+00 |
| | SOFC 78% Load | 1.79E+00 |
| | SOFC 68% Load | 2.08E+00 |
| | SOFC 62% Load | 2.43E+00 |

**Table 3-24: LC PE consumption factor of gas boiler producing unit heating energy.**

| System | PE ($kWh/kWh_t$) | Non-renewable Resources ($kWh/kWh_t$) | Renewable Resources ($kWh/kWh_t$) | Wastes ($kWh/kWh_t$) |
|---|---|---|---|---|
| **Gas Boiler** | 1.18E+00 | 1.18E+00 | 2.51E-04 | 1.01E-03 |

### 3.5.2 Global Warming Potential

The LCA results show that the GWP indicator factors increase with decreasing part load operation for both MT and ICE cogeneration systems. In other words, both the MT and ICE have the lowest GWP impacts when operated at full load because the power to heat ratios of these cogeneration systems decrease with decreasing part load operation, and therefore result in higher emissions due to inefficient fuel combustion at lower part load operation. Table 3-25 shows the GWP indicator values and Figure 3-8 shows an illustration of these values resulting from the energy systems when used to produce unit output of electrical energy.

The NGCC has the lowest GWP value impact compared to all systems. The GWP indicator value resulting from the average electric process is about 77% higher than that of the NGCC and is comparable to GWP values of the MT operating at full load, because the electrical efficiency ratio of the MT and the average electric grid are comparable. The ICE cogeneration system has the lowest GWP compared to the other cogeneration systems. Table 3-26 shows the GWP indicator value for the gas boiler when used to produce a unit output of thermal energy.

**Table 3-25: GWP emission factors for energy systems producing unit power output.**

| System | | $CO_2$ Equivalent | $CO_2$ | $CH_4$ | $N_2O$ | Perfluoro-methane | Perfluoro-ethane |
|---|---|---|---|---|---|---|---|
| | | | | | (kg/kWh$_e$) | | |
| MT | MT 100%Load | 7.50E-01 | 7.33E-01 | 7.52E-04 | 1.55E-06 | 5.03E-11 | 6.32E-12 |
| | MT 75%Load | 7.95E-01 | 7.70E-01 | 1.16E-03 | 1.68E-06 | 5.43E-11 | 6.82E-12 |
| | MT 50%Load | 1.07E+00 | 8.96E-01 | 8.09E-03 | 2.03E-06 | 6.51E-11 | 8.18E-12 |
| | MT 25%Load | 1.48E+00 | 1.38E+00 | 4.51E-03 | 3.10E-06 | 9.81E-11 | 1.23E-11 |
| ICE | ICE 100% Load | 6.20E-01 | 5.39E-01 | 3.84E-03 | 1.22E-06 | 4.23E-11 | 5.31E-12 |
| | ICE 75% Load | 6.75E-01 | 5.92E-01 | 3.91E-03 | 1.34E-06 | 4.60E-11 | 5.78E-12 |
| | ICE 50% Load | 7.64E-01 | 6.77E-01 | 4.14E-03 | 1.53E-06 | 4.95E-11 | 6.22E-12 |
| SOFC | SOFC 104% Load | 1.05E+00 | 1.03E+00 | 5.87E-04 | 1.35E-06 | 7.53E-11 | 9.46E-12 |
| | SOFC 100% Load | 1.02E+00 | 1.01E+00 | 5.75E-04 | 1.33E-06 | 7.45E-11 | 9.36E-12 |
| | SOFC 93% Load | 9.61E-01 | 9.49E-01 | 5.41E-04 | 1.25E-06 | 7.23E-11 | 9.09E-12 |
| | SOFC 85% Load | 9.41E-01 | 9.30E-01 | 5.31E-04 | 1.23E-06 | 7.17E-11 | 9.01E-12 |
| | SOFC 78% Load | 9.23E-01 | 9.11E-01 | 5.21E-04 | 1.21E-06 | 7.10E-11 | 8.93E-12 |
| | SOFC 68% Load | 9.23E-01 | 9.11E-01 | 5.21E-04 | 1.21E-06 | 7.10E-11 | 8.93E-12 |
| | SOFC 62% Load | 9.05E-01 | 8.94E-01 | 5.11E-04 | 1.19E-06 | 7.04E-11 | 8.85E-12 |
| | US Average Electric | 7.87E-01 | 7.36E-01 | 1.82E-03 | 4.03E-05 | 2.83E-09 | 3.55E-10 |
| | NGCC | 4.45E-01 | 4.31E-01 | 4.56E-04 | 1.21E-05 | 2.86E-11 | 3.59E-12 |

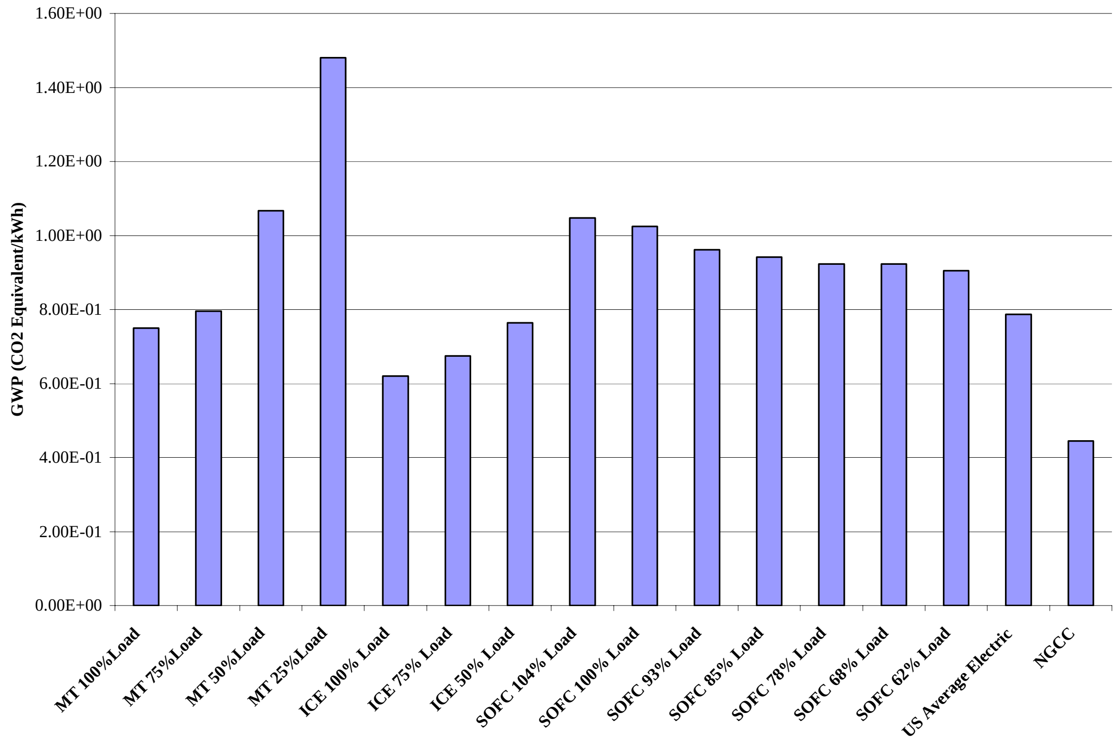



**Figure 3-8: GWP emission factors for energy systems producing unit power output.**

**Table 3-26: GWP emission factors for gas boiler producing unit heating energy.**

| System | $CO_2$ Equivalent | $CO_2$ | $CH_4$ | $N_2O$ | Perfluoro-methane | Perfluoro-ethane |
|---|---|---|---|---|---|---|
| | | | ($kg/kWh_t$) | | | |
| Gas Boiler | 2.40E-01 | 2.35E-01 | 2.24E-04 | 1.55E-06 | 1.52E-11 | 1.91E-12 |

Figure 3-9 shows the major gas component contributions to the total GWP indicator value of the ICE cogeneration system operating at 100% load. $CO_2$ emissions contribute about 87% to the total GWP value of the ICE system; 95% of the $CO_2$ emissions originate from fuel combustion from the ICE cogeneration system, 4% originate from the gas compressor used in gas transportation in pipelines and the remaining 1% of the emissions are associated with upstream manufacturing processes of the ICE. $CH_4$ emissions contribute about 13% of the total GWP value of the ICE system, where 85% of the emissions originate from the fuel combustion process from the ICE, 14% from gas processing and extraction and the remaining 1% of the emissions result from upstream processes associated with ICE manufacturing. $N_2O$ emissions contribute only 0.06% of the total GWP value, where 74% of the $N_2O$ emissions originate from the gas compressor and the remaining 26% of the emissions result from upstream electric production processes used for ICE manufacturing.

Figure 3-10 shows the major gas contribution to the total GWP indicator value of the MT cogeneration system operating at 100% load. $CO_2$ emissions contribute about 98% to the total GWP value of the MT system; 95% of the $CO_2$ emissions originate from fuel combustion from the MT cogeneration system, 3% originate from the gas compressor used in gas transportation in pipelines and the remaining 2% of the emissions are associated with upstream manufacturing processes of the MT. $CH_4$ emissions contribute about 2% of the total GWP value of the ICE system, where 45% of the emissions originate from the from gas processing and an equal share from gas extraction, 4% from fugitive emissions from gas pipeline and the remaining 6% of the emissions result from upstream processes associated with MT manufacturing while the fuel combustion due to MT contributes less than 1% of the total $CH_4$ emissions. $N_2O$ emissions contribute only 0.06% of the total GWP value, where 73% of the $N_2O$ emissions originate from the gas compressor and the remaining 23% of the emissions result from upstream electric production processes used for MT manufacturing.

The GWP indicator factors for the SOFC system are approximately constant at the different part loads but decrease slightly with decreasing part load operation. However, the SOFC has the highest GWP values while the MT system has the lowest GWP values compared to the other cogeneration systems. The reason for the high GWP value for the SOFC is because of the high $CO_2$ emissions relative to the MT and ICE cogeneration systems. The high $CO_2$ emission value of the SOFC cogeneration system is because of the majority of $CO_2$ emissions originate from the steam reforming process of natural gas which is responsible for 97% of the total $CO_2$ emissions from the SOFC cogeneration process. Figure 3-11 shows the major gas contribution to the total GWP indicator value of the SOFC cogeneration system operating at 100% load. $CO_2$ is the major gas contributing about 99% of the total value of GWP of the SOFC, most of which originates from the steam reforming process and only 2% of the $CO_2$ total emissions originate from the gas compressor used for gas transportation in pipelines while the rest of the emissions originate from other upstream extraction and manufacturing possesses. $CH_4$ contributes only 1% to the total value of GWP emission factor of the SOFC cogeneration system; 43% of the $CH_4$ emissions originate from the natural gas extraction process and an equal share from gas processing process while the remaining 14% originate from coal extraction processes associated with the electric generation process used in the SOFC manufacturing process. $N_2O$ emissions constitute only 0.0004% of the total GWP value; 63% of the $N_2O$ emissions originate from the gas compressor, 25% are due to emissions associated with electric production used in the SOFC manufacturing process and the remaining 12% of the emissions come from the manufacturing process of the SOFC.

Figure 3-12 shows the major gas contribution to the total GWP indicator value of the NGCC power plant. $CO_2$ emissions contribute about 97% to the total GWP value for the NGCC; 95% of the $CO_2$ emissions originate from fuel combustion from the NGCC, 3% originate from the gas compressor used in gas transportation in pipelines and the remaining 2% of the emissions are associated with upstream manufacturing processes. $CH_4$ emissions contribute about 2% of the total GWP value for the NGCC, where 43% of the emissions originate from the from gas processing and an equal share from gas extraction, 7% of the emissions originate from the NGCC fuel combustion process, 3% from fugitive emissions from gas pipeline and the remaining 4% of the emissions result from upstream processes associated with manufacturing. $N_2O$ emissions contribute only about 1% of the total GWP value, where 93% of the $N_2O$ emissions originate from fuel combustion from the NGCC, 5% of the emissions come from the gas compressor and the remaining 2% of the emissions result from upstream manufacturing processes.

Figure 3-13 shows the major gas contribution to the total GWP indicator value of the USA average electric generation grid. $CO_2$ emissions contribute about 94% to the total GWP value; 75% of the $CO_2$ emissions originate from power production from the coal-driven steam turbine power plant, 14% of the $CO_2$ emissions originate from power production from the gas turbine power plant, 5% of the $CO_2$ emissions originate from power production from the waste-driven steam turbine power plant, 2% of the $CO_2$ emissions originate from power production from the oil-driven steam turbine power plant, and the remaining 4% are associated with upstream fuel production and transportation processes. $CH_4$ emissions contribute about 5% of the total GWP value, where about 91% of the $CH_4$ emissions originate from coal extraction process, 2.5% of the $CH_4$ emissions result from gas processing, 2.5% of the $CH_4$ emissions originate from onshore gas extraction process, and the remaining 4% of the $CH_4$ emissions originate mainly from other upstream processes associated with the extraction and processing of non-renewable fuels. $N_2O$ emissions contribute only about 1% of the total GWP value, where 79% of the $N_2O$ emissions originate from coal-driven steam turbine power plant, 12% of the $N_2O$ emissions originate from the gas turbine power plant, 3% of the $N_2O$ emissions originate from waste-driven steam turbine power plant, about 2% of the $N_2O$ emissions originate from the oil-driven steam turbine power plant and the remaining 4% of the $N_2O$ emissions originate from the other upstream fuel production and processing stages.

Figure 3-14 shows the major gas contribution to the total GWP indicator value of the gas boiler. $CO_2$ emissions contribute about 97% to the total GWP value for the gas boiler; 95% of the $CO_2$ emissions originate from fuel combustion from the gas boiler, 3% originate from the gas compressor used in gas transportation in pipelines and the remaining 2% of the emissions are associated with upstream manufacturing processes. $CH_4$ emissions contribute about 2% of the total GWP value for the NGCC, where 45% of the emissions originate from the from gas processing and an equal share from gas extraction, 4% from fugitive emissions from gas pipeline and the remaining 6% of the emissions result from upstream processes associated with manufacturing. $N_2O$ emissions contribute only about 0.2% of the total GWP value, where 70% of the $N_2O$ emissions originate from fuel combustion from the gas boiler, 21% of the emissions come from the gas compressor and the remaining 9% of the emissions result from upstream manufacturing processes.

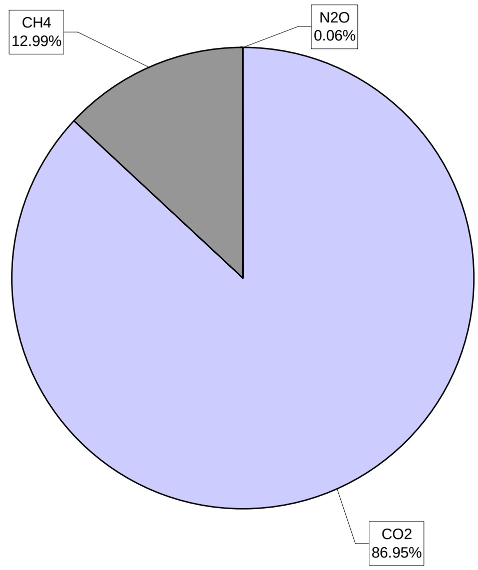



**Figure 3-9: Emissions contributing to GWP from ICE producing unit power output.**

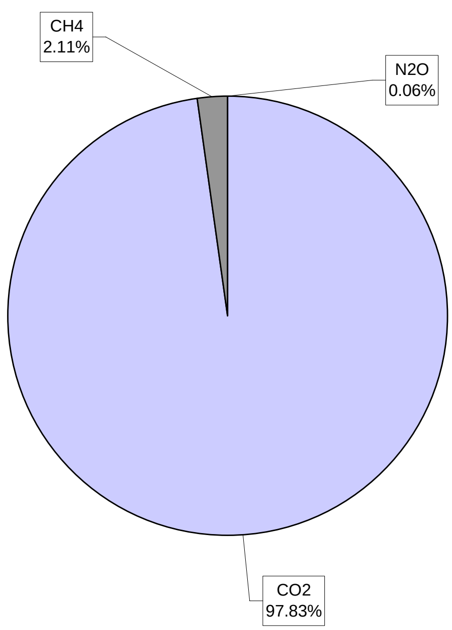



**Figure 3-10: Emissions contributing to GWP from MT producing unit power output.**

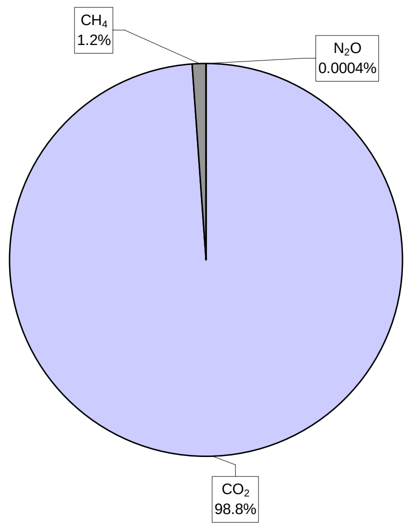



**Figure 3-11: Emissions contributing to GWP from SOFC producing unit power output.**

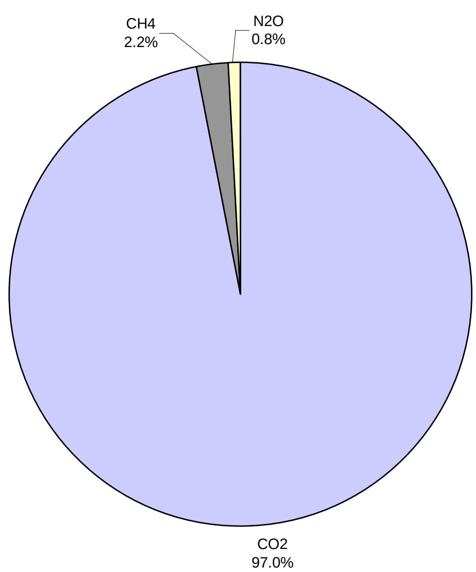



**Figure 3-12: Emissions contributing to GWP from NGCC producing unit power output.**

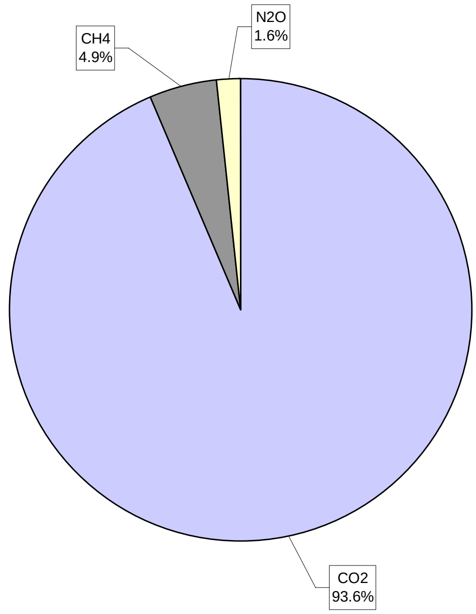



**Figure 3-13: Emission factors contributing to GWP from the average electric grid producing unit power output.**

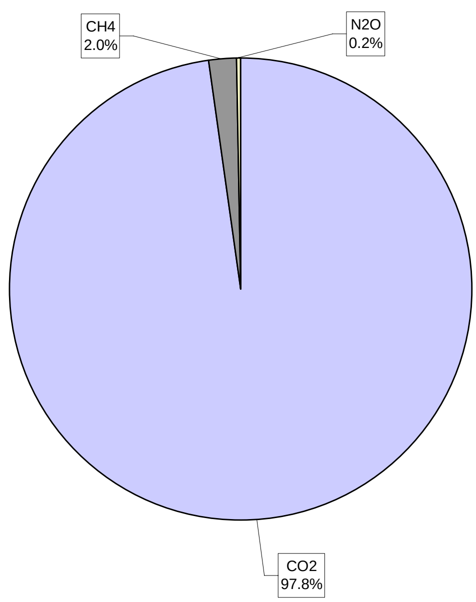



**Figure 3-14: Emission factors contributing to GWP from gas boiler producing unit heating energy.**

### 3.5.3 Acidification Potential

The LCA results show that the AP indicator factors increase with decreasing part load operation for both MT and ICE cogeneration systems, in other words, both the MT and ICE have the lowest AP impacts when operated at full load because of the power to heat ratios of these cogeneration systems decrease with decreasing part load operation and therefore resulting in higher emissions due to inefficient fuel combustion at lower part load operation. Table 3-27 shows the AP indicator values and Figure 3-15 shows an illustration of these values resulting from the energy systems when used to produce unit output of electrical energy. The high AP indicator values of the ICE cogeneration system compared to the MT and the SOFC cogeneration systems (about 92% higher) are because of the higher $NO_x$ emissions (a major contributor to AP) from the ICE cogeneration system relative to the MT and SOFC systems. The average electric grid has a comparable AP indicator value to the ICE cogeneration system, whereas the AP value of the NGCC is about 84% lower than that of the average electric grid. Table 3-28 shows the AP indicator value for the gas boiler when used to produce a unit output of thermal energy.

**Table 3-27: LC AP emission factors for energy systems producing unit power output.**

| | System | AP | $SO_2$ | $NO_x$ | HCl | HF |
|---|---|---|---|---|---|---|
| MT | MT 100%Load | 1.82E-04 | 1.83E-05 | 2.34E-04 | 4.68E-07 | 2.32E-08 |
| | MT 75%Load | 1.99E-04 | 1.98E-05 | 2.57E-04 | 5.07E-07 | 2.51E-08 |
| | MT 50%Load | 2.60E-04 | 2.38E-05 | 3.38E-04 | 6.13E-07 | 3.04E-08 |
| | MT 25%Load | 4.67E-04 | 3.59E-05 | 6.17E-04 | 9.35E-07 | 4.64E-08 |
| ICE | ICE 100% Load | 2.12E-03 | 1.34E-05 | 3.03E-03 | 3.68E-07 | 1.82E-08 |
| | ICE 75% Load | 2.22E-03 | 1.45E-05 | 3.16E-03 | 4.04E-07 | 2.00E-08 |
| | ICE 50% Load | 2.23E-03 | 1.57E-05 | 3.18E-03 | 4.61E-07 | 2.29E-08 |
| SOFC | SOFC 104% Load | 1.23E-04 | 2.22E-05 | 1.44E-04 | 5.72E-07 | 3.90E-08 |
| | SOFC 100% Load | 1.21E-04 | 2.20E-05 | 1.41E-04 | 5.64E-07 | 3.86E-08 |
| | SOFC 93% Load | 1.15E-04 | 2.15E-05 | 1.34E-04 | 5.43E-07 | 3.76E-08 |
| | SOFC 85% Load | 1.13E-04 | 2.13E-05 | 1.31E-04 | 5.36E-07 | 3.73E-08 |
| | SOFC 78% Load | 1.12E-04 | 2.12E-05 | 1.29E-04 | 5.30E-07 | 3.69E-08 |
| | SOFC 68% Load | 1.12E-04 | 2.12E-05 | 1.29E-04 | 5.30E-07 | 3.69E-08 |
| | SOFC 62% Load | 1.10E-04 | 2.10E-05 | 1.27E-04 | 5.24E-07 | 3.66E-08 |
| US Average Electric | | 2.61E-03 | 7.77E-04 | 2.55E-03 | 5.78E-05 | 2.87E-06 |
| NGCC | | 4.14E-04 | 1.04E-05 | 5.80E-04 | 2.67E-07 | 1.41E-08 |

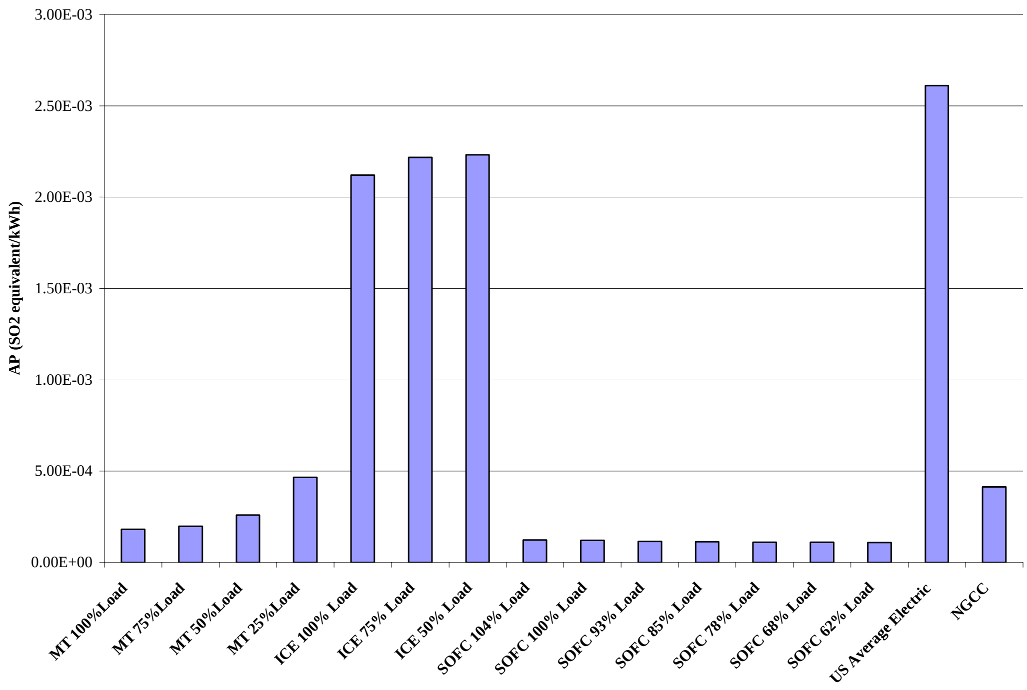



**Figure 3-15: LC AP emission factors for energy systems producing unit power output.**

**Table 3-28: LC AP emission factor for gas boiler producing unit heating energy output.**

| System | AP | $SO_2$ | $NO_x$ | HCl | HF |
|---|---|---|---|---|---|
| Gas Boiler | 9.89E-05 | 4.83E-06 | 1.35E-04 | 1.38E-07 | 6.85E-09 |

Figure 3-16 shows the major gas contribution to the total AP indicator value of the ICE cogeneration system operating at 100% load. $NO_x$ emissions contribute about 99% to the total AP value of the ICE system; 96% of the $NO_x$ emissions originate from fuel combustion from the ICE cogeneration system, 3% originate from the gas compressor used in gas transportation in pipelines and the remaining 1% of the emissions are associated with upstream manufacturing processes of the ICE. $SO_2$ emissions contribute about 0.63% of the total AP value of the ICE system, where 20% of the emissions originate from the fuel combustion process from the ICE and the remaining 80% of the emissions result from upstream processes associated with ICE manufacturing and fuel production. HCl and HF have low contribution to the total AP value, 0.015% and 0.001%, respectively. The majority of HCl and HF emissions originate from upstream coal production processes used in electricity generation which is used in the manufacturing process of the ICE cogeneration system.

Figure 3-17 shows the major gas contribution to the total AP indicator value of the MT cogeneration system operating at 100% load. $NO_x$ emissions contribute about 90% to the total AP value of the MT system; 29% of the $NO_x$ emissions originate from fuel combustion from the MT cogeneration system, 57% originate from the gas compressor and the remaining 14% of the emissions are associated with upstream manufacturing processes of the MT and fuel production. $SO_2$ emissions contribute about 10% of the total AP value of the MT system, where 32% of the emissions originate from the fuel combustion process from the MT and the remaining 68% of the emissions result from upstream processes associated with MT manufacturing and fuel production. HCl and HF have low contribution to the total AP value, 0.2% and 0.02%, respectively. The majority of HCl and HF emissions originate from upstream coal production processes used in electricity generation which is used in the manufacturing process of the MT cogeneration system.

Figure 3-18 shows the major gas contribution to the total AP indicator value of the SOFC cogeneration system operating at 100% load. $NO_x$ emissions contribute about 81% to the total

AP value of the SOFC system; only 0.4% of the NOx emissions are due to the SOFC cogeneration system fuel combustion process, while 69% of the $NO_x$ emissions originate from the gas compressor and the remaining 30.6% of the emissions are associated with upstream manufacturing processes of the SOFC and fuel production. $SO_2$ emissions contribute about 18% of the total AP value of the SOFC system, where the emissions result from upstream processes associated with SOFC manufacturing and fuel production. HCl and HF have a low contribution to the total AP value, 0.4% and 0.1%, respectively. The majority of HCl and HF emissions originate from upstream coal production processes used in electricity generation; which is used in the manufacturing process of the SOFC cogeneration system.

Figure 3-19 shows the major gas contribution to the total AP indicator value of the NGCC power plant. $NO_x$ emissions contribute about 97% to the total AP value of the NGCC; 83% of the $NO_x$ emissions are due to the NGCC fuel combustion process for electric production, while 13% of the $NO_x$ emissions originate from the gas compressor and the remaining 4% of the emissions are associated with upstream manufacturing processes of the NGCC and fuel production. $SO_2$ emissions contribute about 2.5% of the total AP value of the NGCC, where 32% of the $SO_2$ emissions are due to the NGCC fuel combustion process for electric production, the remaining 68% result from upstream processes associated with NGCC manufacturing and fuel production. HCl and HF have a low contribution to the total AP value, 0.06% and 0.01%, respectively. The majority of HCl and HF emissions originate from upstream coal production processes used in electricity generation which is used in the manufacturing process of the NGCC cogeneration system.

Figure 3-20 shows the major gas contribution to the total AP indicator value of the average electric grid. $NO_x$ emissions contribute about 68% to the total AP value of the average electric grid; 59% of the $NO_x$ emissions are due to electric production from the coal steam-driven power plant, 30% are due to electric production from the gas-driven power plant, 4% are due to electric production from the waste steam-driven power plant, and the remaining 7% of the emissions are associated with other upstream fuel and material production. $SO_2$ emissions contribute about 30% of the total AP value of the average electric, where 80% of the $SO_2$ emissions are due to electric production from the coal steam-driven power plant and the remaining 20% result from other upstream processes associated with fuel and material production. HCl and HF have low a contribution to the total AP value, 1.95% and 0.18%, respectively. The majority of HCl and HF emissions originate from upstream coal production processes used in electricity generation.

Figure 3-21 shows the major gas contribution to the total AP indicator value of the gas boiler. $NO_x$ emissions contribute about 95% to the total AP value of the gas boiler; 64% of the $NO_x$ emissions are due to the gas boiler fuel combustion process for heat production, while 29% of the $NO_x$ emissions originate from the gas compressor and the remaining 7% of the emissions are associated with upstream manufacturing processes of the gas boiler and fuel production. $SO_2$ emissions contribute about 5% of the total AP value of the gas boiler, where 21% of the $SO_2$ emissions are due to the gas boiler fuel combustion process; the remaining 79% result from upstream processes associated with the boiler manufacturing and fuel production. HCl and HF have a low contribution to the total AP value, 0.12% and 0.01%, respectively. The majority of HCl and HF emissions originate from upstream coal production processes used in electricity generation which is used in the manufacturing process of the gas boiler cogeneration system and fuel delivery.

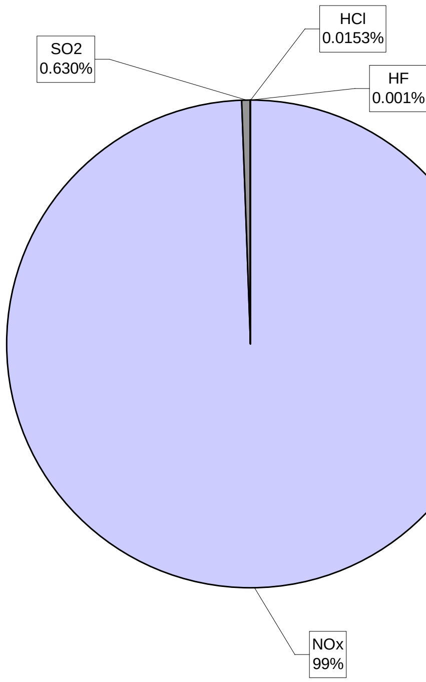



**Figure 3-16: Emissions contributing to AP from ICE producing unit power output.**

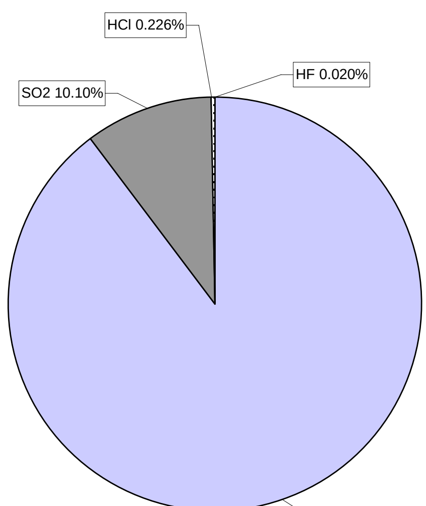



**Figure 3-17: Emissions contributing to AP from MT producing unit power output.**

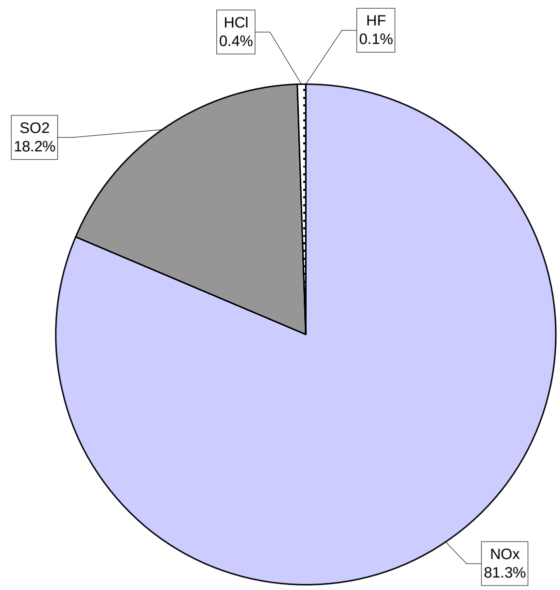



**Figure 3-18: Emissions contributing to AP from SOFC producing unit power output.**

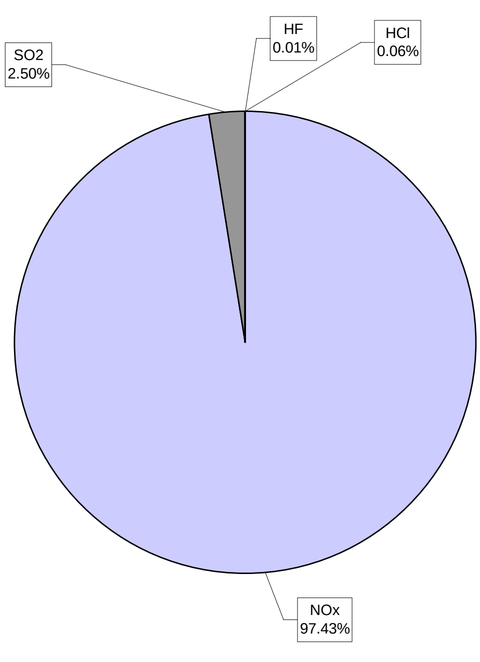



**Figure 3-19: Emissions contributing to AP from NGCC producing unit power output.**

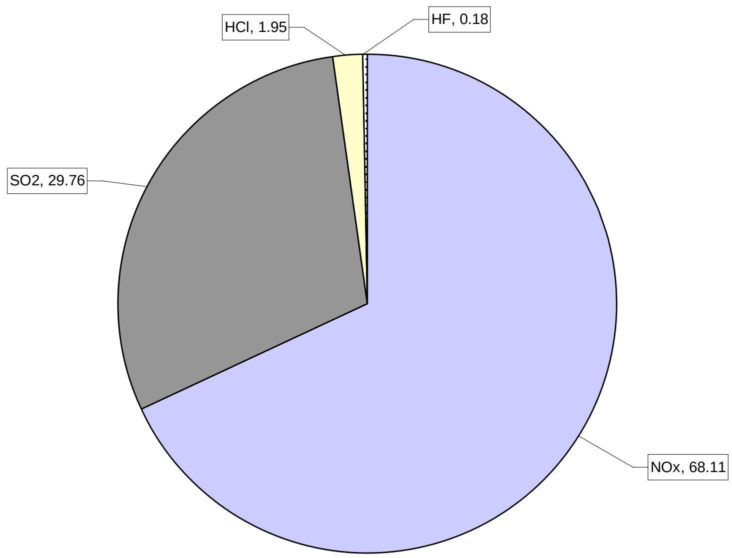



**Figure 3-20: Emissions contributing to AP from the average electric grid producing unit power output.**

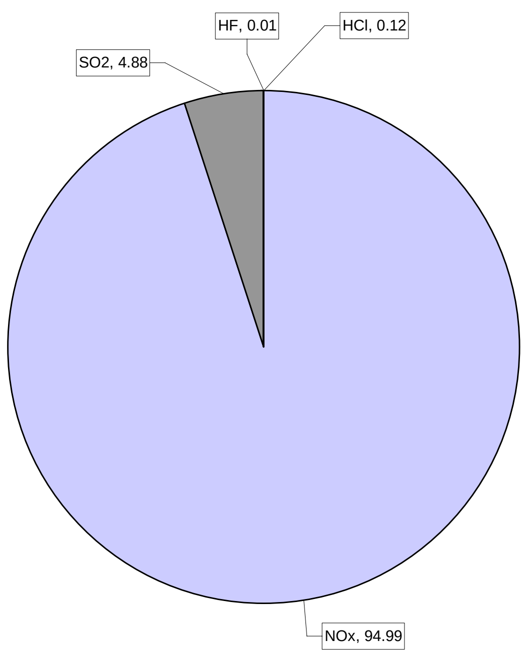



**Figure 3-21: Emissions contributing to AP from gas boiler producing unit heating energy output.**

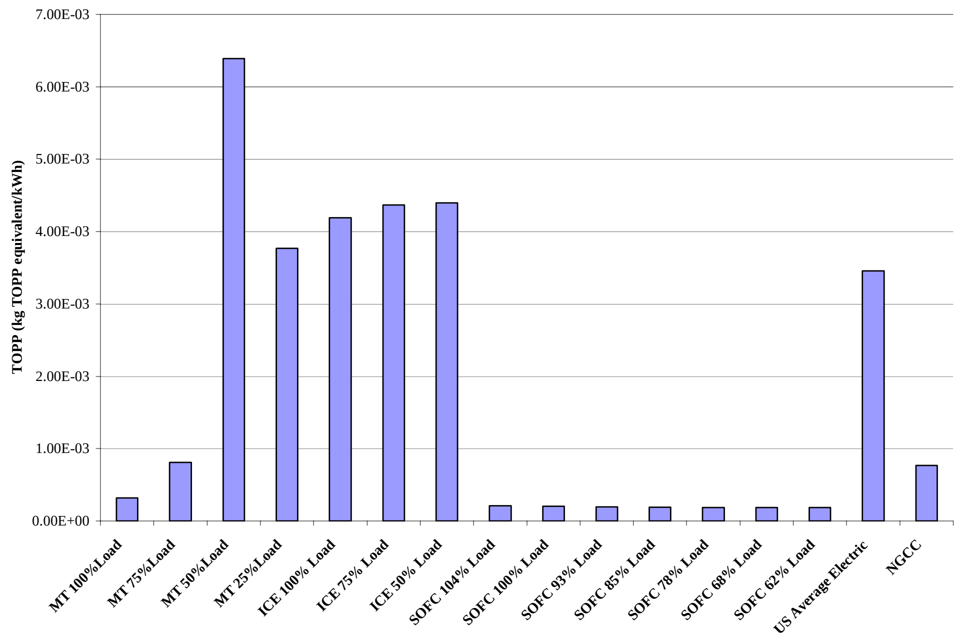



**Figure 3-22: LC TOPP emission factors from energy systems producing unit power output.**

### 3.5.4 Tropospheric Ozone Precursor Potential

The LCA results show that the TOPP indicator factors increase with decreasing part load operation for ICE cogeneration systems. In other words, the ICE has the lowest TOPP impacts when operated at full load. However, the TOPP indicator factor values for the MT cogeneration system show a different trend: the values are lowest when the MT cogeneration system is operated at 100% and 75% part load, but the values increase by almost seven times when the MT is operated at 50% load. The indicator values decrease almost by half at 25% load operation relative to the values obtained at 50% part load operation. This was because the CO, NMVOC and $CH_4$ values showed inverse relations to $NO_x$: as the $NO_x$ values increased with decreasing part load operation the CO, NMVOC and $CH_4$ values decreased from 50% to 25% part load operation of the MT resulting in the irregular trend of the TOPP values with part load operation.

Table 3-29 shows the TOPP indicator values and Figure 3-22 shows an illustration of these values resulting from the energy systems when used to produce unit output of electrical energy. The high TOPP indicator values of the ICE cogeneration system compared to the MT and the SOFC cogeneration systems (about 92% higher) is because of the higher NOx emissions (a major contributor to TOPP) from the ICE cogeneration system relative to the MT and the SOFC systems. However, because the value of CO, CH4 and NMVOC were relatively high for the MT cogeneration system operating at 50% part load, the resultant TOPP value was higher than any of the other systems. The average electric has a comparable TOPP indicator value to the ICE cogeneration system, whereas the TOPP value of the NGCC is about 78% lower than that of the average electric grid. Table 3-30 shows the TOPP indicator value for the gas boiler when used to produce a unit output of heating.

**Table 3-29: LC TOPP emission factors from energy systems producing unit power output.**

| System | | TOPP | NOx | CO | NMVOC | CH4 |
|---|---|---|---|---|---|---|
| MT | MT 100%Load | 3.19E-04 | 2.34E-04 | 1.46E-04 | 7.69E-06 | 7.52E-04 |
| | MT 75%Load | 8.11E-04 | 2.57E-04 | 2.30E-03 | 2.27E-04 | 1.16E-03 |
| | MT 50%Load | 6.39E-03 | 3.38E-04 | 1.04E-02 | 4.72E-03 | 8.09E-03 |
| | MT 25%Load | 3.77E-03 | 6.17E-04 | 9.17E-03 | 1.94E-03 | 4.51E-03 |
| ICE | ICE 100% Load | 4.19E-03 | 3.03E-03 | 1.17E-03 | 3.16E-04 | 3.84E-03 |
| | ICE 75% Load | 4.37E-03 | 3.16E-03 | 1.18E-03 | 3.23E-04 | 3.91E-03 |
| | ICE 50% Load | 4.40E-03 | 3.18E-03 | 1.26E-03 | 3.18E-04 | 4.14E-03 |
| SOFC | SOFC 104% Load | 2.08E-04 | 1.44E-04 | 1.61E-04 | 6.59E-06 | 5.87E-04 |
| | SOFC 100% Load | 2.04E-04 | 1.41E-04 | 1.59E-04 | 6.48E-06 | 5.75E-04 |
| | SOFC 93% Load | 1.94E-04 | 1.34E-04 | 1.55E-04 | 6.17E-06 | 5.41E-04 |
| | SOFC 85% Load | 1.91E-04 | 1.31E-04 | 1.54E-04 | 6.08E-06 | 5.31E-04 |
| | SOFC 78% Load | 1.87E-04 | 1.29E-04 | 1.53E-04 | 5.99E-06 | 5.21E-04 |
| | SOFC 68% Load | 1.87E-04 | 1.29E-04 | 1.53E-04 | 5.99E-06 | 5.21E-04 |
| | SOFC 62% Load | 1.85E-04 | 1.27E-04 | 1.51E-04 | 5.90E-06 | 5.11E-04 |
| US Average Electric | | 3.46E-03 | 2.55E-03 | 6.30E-04 | 2.48E-04 | 1.82E-03 |
| NGCC | | 7.69E-04 | 5.80E-04 | 1.67E-04 | 3.71E-05 | 4.56E-04 |

**Table 3-30: LC TOPP emission factors from the gas boiler producing a unit heating output.**

| System | TOPP | NOx | CO | NMVOC | CH4 |
|---|---|---|---|---|---|
| Gas Boiler | 2.09E-04 | 1.35E-04 | 1.74E-04 | 2.25E-05 | 2.24E-04 |

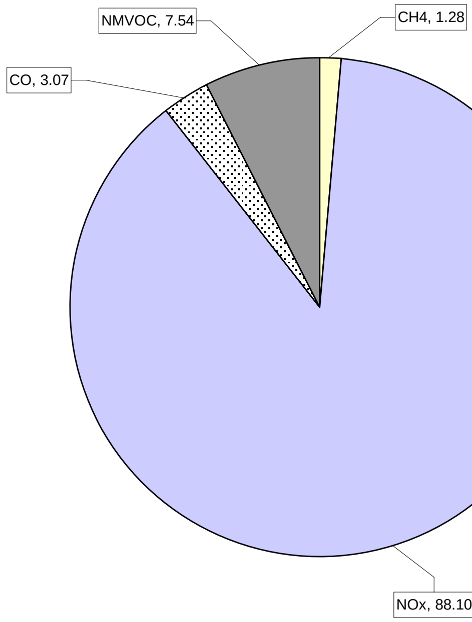



**Figure 3-23: Emissions contributing to TOPP from ICE producing unit power.**

Figure 3-23 shows the major gas contribution to the total TOPP indicator value of the ICE cogeneration system operating at 100% load. $NO_x$ emissions contribute about 88% to the total TOPP value of the ICE system. The origins of $NO_x$ emissions are the same as discussed in the AP section. NMVOC emissions contribute about 8% to the total TOPP value of the ICE system; where 98% of the emissions originate from fuel combustion in the ICE cogeneration system for electric production, only 1% from the gas compressor and the remaining 1% of the emissions originate from other upstream processes associated with fuel and material production and manufacturing. CO contribute 3% to the total TOPP value of the ICE system; where 93% of the emissions also originate from fuel combustion from the ICE, about 3% from the gas compressor and the remainder 4% originate from upstream processes. $CH_4$ contributes only about 1% to the total TOPP value of the ICE system. The origins of $CH_4$ are the same as discussed in the GWP section.

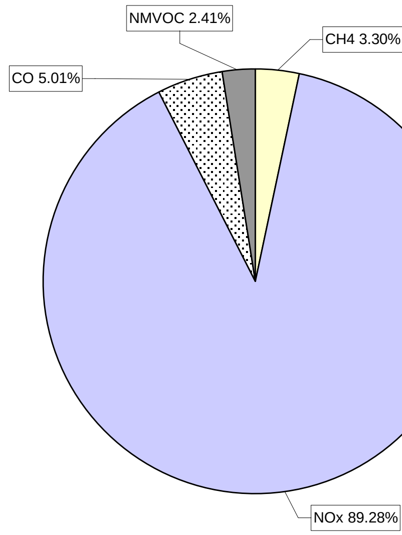



**Figure 3-24: Emissions contributing to TOPP from MT producing a unit power output.**

Figure 3-24 shows the major gas contribution to the total TOPP indicator value of the MT cogeneration system operating at 100% load. $NO_x$ emissions contribute about 89% to the total TOPP value of the MT system. The origins of $NO_x$ emissions are the same as discussed in the AP section. NMVOC emissions contribute about 2% to the total TOPP value of the MT system; where 11% of the emissions originate from fuel combustion in the MT cogeneration system for electric production, 50% from the gas compressor and the remaining 39% of the emissions originate from other upstream processes associated with fuel and material production and manufacturing. CO contribute 5% to the total TOPP value of the MT system; where 32% of the emissions also originate from fuel combustion from the MT, about 26% from the gas compressor and the remainder 42% originate from upstream processes. $CH_4$ contributes only about 3% to the total TOPP value of the MT system. The origins of $CH_4$ are the same as discussed in the GWP section.

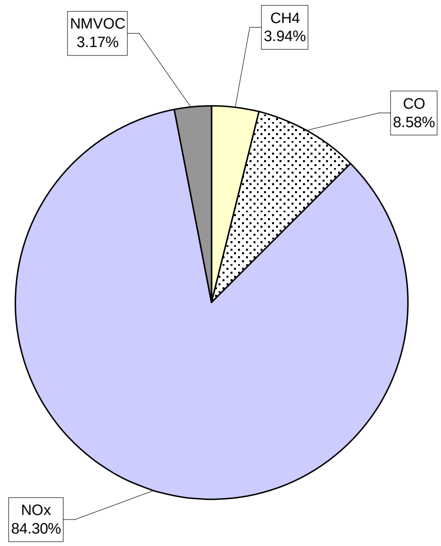



**Figure 3-25: Emissions contributing to TOPP from the SOFC producing a unit power output.**

Figure 3-25 shows the major gas contribution to the total TOPP indicator value of the SOFC cogeneration system operating at 100% load. $NO_x$ emissions contribute about 84% to the total TOPP value of the SOFC system. The origins of $NO_x$ emissions are the same as discussed in the AP section. NMVOC emissions contribute about 3% to the total TOPP value of the SOFC system; where 43% of the emissions originate from the gas compressor, about 26% from electric generation processes used in the manufacturing process of the SOFC, 7% from fugitive emissions from the gas pipeline and the remainder 24% of the emissions originate from other upstream processes associated with fuel and material production and manufacturing. CO contribute 9% to the total TOPP value of the SOFC system; where 26% of the emissions also originate from heat production used in the manufacturing process of the SOFC, about 26% of the emissions result from steel production processes used in the manufacturing process of the SOFC, 18 % from the gas compressor and the remainder 30% originate from upstream processes. $CH_4$ contributes only about 4% to the total TOPP value of the SOFC system. The origins of $CH_4$ are the same as discussed in the GWP section.

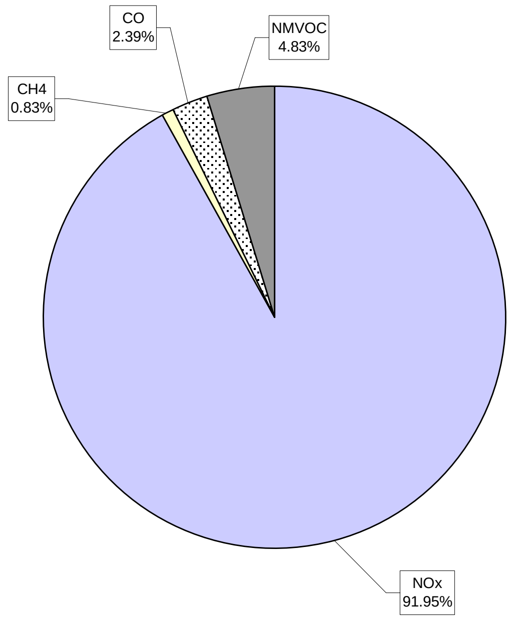



**Figure 3-26: Emissions contributing to TOPP from the NGCC producing a unit power output.**

Figure 3-26 shows the major gas contribution to the total TOPP indicator value of the NGCC power plant. $NO_x$ emissions contribute about 92% to the total TOPP value of the NGCC. The origins of $NO_x$ emissions are the same as discussed in the AP section. NMVOC emissions contribute about 5% to the total TOPP value of the NGCC; where 90% of the emissions originate from fuel combustion for power generation from the NGCC power plant, 5% from the gas compressor and the remainder 5% of the emissions originate from other upstream processes associated with fuel and material production and manufacturing. CO contribute 2% to the total TOPP value of NGCC; where 67% of the emissions also originate from fuel combustion for power generation from the NGCC power plant, 13 % from the gas compressor and the remainder 20% of the emissions originate from upstream processes. $CH_4$ contributes only about 1% to the total TOPP value of the NGCC. The origins of $CH_4$ are the same as discussed in the GWP section.

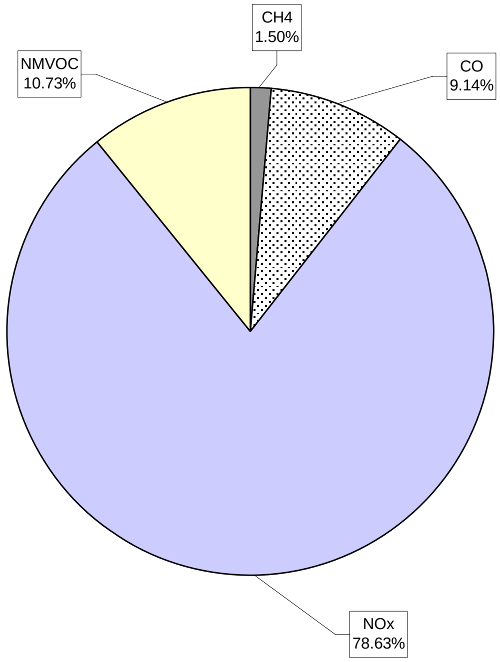



**Figure 3-27: Emissions contributing to TOPP from the average electric grid producing a unit power output.**

Figure 3-27 shows the major gas contribution to the total TOPP indicator value of the average electric grid. $NO_x$ emissions contribute about 90% to the total TOPP value of the average electric grid. The origins of $NO_x$ emissions are the same as discussed in the AP section. NMVOC emissions contribute about 7% to the total TOPP value of the average electric grid; where 45% of the emissions originate from fuel combustion for power generation from the coal steam-driven power plant, 31% of the emissions originate from fuel combustion for power generation from the gas-driven power plant, 16% of the emissions originate from fuel combustion for power generation from the waste steam-driven power plant and the remaining 8% of the emissions originate from other upstream processes associated with fuel and material production and manufacturing. CO contribute 2% to the total TOPP value of the average electric grid; where 35% of the CO emissions originate from fuel combustion for power generation from the coal steam-driven power plant, 25% of the emissions originate from fuel combustion for power generation from the gas-driven power plant, 15% from process heat production and the remainder 25% of the emissions originate from other upstream electric generation and manufacturing processes. $CH_4$ contributes only about 0.7% to the total TOPP value of the average electric grid. The origins of $CH_4$ are the same as discussed in the GWP section.

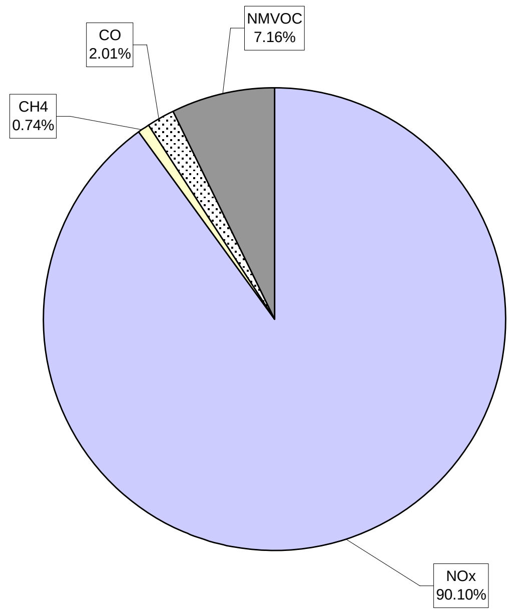



**Figure 3-28: Emissions contributing to TOPP from the gas boiler producing a unit heating output.**

Figure 3-28 shows the major gas contribution to the total TOPP indicator value of the gas boiler. $NO_x$ emissions contribute about 79% to the total TOPP value of the average electric grid. The origins of $NO_x$ emissions are the same as discussed in the AP section. NMVOC emissions contribute about 11% to the total TOPP value of the average gas boiler; where 91% of the emissions originate from fuel combustion by the gas boiler, 5% of the emissions originate from the gas compressor and the remaining 4% of the emissions originate from other upstream processes associated with fuel and material production and manufacturing. CO contribute 9% to the total TOPP value of the gas boiler; where 83% of the CO emissions originate from fuel combustion by the gas boiler, 6% from the gas compressor and the remainder 11% originate from other upstream electric generation and manufacturing processes. $CH_4$ contributes only about 2% to the total TOPP value of the gas boiler. The origins of $CH_4$ are the same as discussed in the GWP section.

# 4.0 LCA OPTIMIZATION MODEL

## 4.1 INTRODUCTION

In building design, some of the fundamental decision making questions relate to what is the most beneficial and cost effective energy source(s) that can be used to meet the energy demand of the building. To answer that question, the decision maker needs to identify the options for energy sources. Depending on the selection criteria, e.g. reduced cost, improved system efficiencies, reduced potential environmental impacts, a design model is required during the design and operation phase to model and simulate the operation of the available options in order to predict the performance of the operating strategies. One way of approaching the problem is to model the available options using linear programming. Linear programming is an effective tool for determining the values of a set of decision variables that can take on a large set of possible values in order to optimize a linear objective subject to linear constraints.

The purpose of developing the LCA optimization model is to predict the most effective energy system options including cogeneration systems and the optimum operational strategies that are economical and can result in minimum life cycle environmental impacts. In previous studies, when emissions are considered in optimization problems, they are usually based on emissions resulting from the operational phase of energy systems (Burer et al., 2003; Wu and Rosen, 1999). LCA provides a tool to assess the cumulative potential environmental impacts that can result from the application of energy systems by considering the various impacts resulting from a certain product throughout its life cycle, i.e., extraction of materials and resources, processing and manufacturing, transportation and use. This is particularly significant when considering the environmental impacts resulting from the manufacturing phase of energy systems, as well as when considering the energy lost during transmission of electricity and emissions during transportation of natural gas in gas pipelines.

The optimization model developed in this research allows for integrating different cogeneration systems with grid-based electric generation systems, heating with gas boilers, and cooling systems (electric and absorption chillers). Electricity can be provided by one or more electric generation source at a specific hour of the day, for example, electricity can be provided by the grid, a microturbine, and/or an ICE. Similarly, heat can be provided by one or more heating source at a specific hour. For example, heating can be provided by a gas boiler, a microturbine, or an ICE. At a specific hour of the day, cooling can be provided by an absorption chiller, driven by heat obtained from a gas boiler or a cogeneration process, and/or an electric chiller, driven by electricity from the grid or a cogeneration process.

The optimization model is developed using mixed integer linear programming to optimize the process of selecting energy systems and the appropriate operating strategy for these systems. The variables consist of continuous and binary variables. Continuous decision variables are used to describe the energy supplied from a particular source, such as power obtained from the grid or a cogeneration process at a certain time, cooling obtained from an electric or absorption chiller, and heating obtained from a gas boiler or a cogeneration process. Also, continuous decision variables are used to determine if excess power and heat is available after the electrical and thermal demand is met. Binary variables (0-1 variables) are used to determine if a particular cogeneration unit is used at a certain time or not. For instance, if a particular cogeneration unit, e.g. a microturbine, operating at a certain percent load, e.g. 50%, is selected at a certain time, the same unit operating at a different part load cannot be selected at that time.

The energy demand consisting of electrical, thermal and cooling loads are known inputs and the values are defined in the model as *parameters*. Energy demand based on hourly loads can be obtained from real time energy use data or it can be simulated using energy simulation tools. Also, the performance characteristics inputs, i.e. efficiencies, capacities and emission factors, of the energy systems are defined as *parameters*.

Linear equations are used to describe the correlations between the capacities and efficiencies of energy systems due to the rated and part load status. The relationships between energy demand and energy supply are formulated as linear equations based on the first law of thermodynamics. These equations are considered as constraints in the optimization model. The objective function of the optimization model is formulated by using the continuous decision variables for energy supply and the emission factors are the coefficients of the decision variable for the energy systems.

Two basic LCA optimization models are developed: the *hourly LCA optimization model* that can be used for long term planning and operational analysis in buildings, and the *simplified yearly LCA optimization model* that can be used for design and short term planning for building operation. The calculation results in finding the optimal values for the decision variables expressing the quantity of electrical, thermal, and cooling energy provided by each system at a particular hour, i.e., the optimum operational strategy. Emission factors obtained from the LCA model are used as coefficients of the decision variables in the objective function when minimizing the environmental impacts. The formulation allows for the minimization of the life cycle emissions and the minimization of primary energy consumption resulting from the production and use of energy.

For design, the model can be used to determine energy system strategies. For design and evaluation of the operation phase, the model can be used to ascertain the most efficient operating strategy to be implemented based upon predicted energy use from hourly building energy data. This improves system performance when compared to a fixed operating strategy such as when following the thermal or electric load of a building. The model could also be useful for making operational decisions when predictions of short-term expected loads are fairly well known. Furthermore, the model can be used to assess alternative building energy use reduction efforts regarding electrical and thermal energy and to determine which alternative might have the best result for the effort invested. Lastly, the model can be used for design and short term planning for cogeneration system operation in building applications and the extended model can be used for long term planning and operational analysis.

AMPL, A Modeling Language for Mathematical Programming (Fourer *et al.*, 2002), is used to formulate the optimization algorithms. The optimization model is solved using a dual simplex algorithm that finds a solution satisfying the optimality conditions (a solution feasible in the constraints), then iterates toward feasibility by using the branch and bound algorithm. CPLEX, an optimization package for linear, network and integer programming, is used in the model implementation.

## 4.2 LCA OPTIMIZATION MODEL DESCRIPTION

The objective of the LCA optimization model is to minimize the life cycle emissions, primary energy use, and capital and operating costs resulting from the use of grid-based and/or cogeneration systems to meet the electrical, thermal and cooling demand of a building. The problems are formulated to address a single objective at a time. The objective function is formulated to minimize each of the following indicators:

- Primary Energy Consumption (PE),
- Global Warming Potential (GWP),
- Acidification Potential (AP),
- Tropospheric Ozone Potential (TOPP),
- Carbon dioxide ($CO_2$),
- Sulfur dioxide ($SO_2$),
- Nitrogen oxides ($NO_X$), and
- Capital and operational costs.

To evaluate the most cost-effective system while considering the potential environmental impacts, the Pareto optimal solutions are evaluated and used to construct the efficient frontier or tradeoff curves with cost [$] on the x-axis and the environmental indicator(s) (life cycle emissions expressed in [kg] and primary energy consumption expressed in [kWh]) on the y-axis.

When determining the tradeoffs between implementing cost-effective operation versus applying techniques that reduce the potential environmental impacts in buildings, optimization is usually performed for multiple objective functions. One way to address this problem is to find the Pareto optimal solutions. Pareto optimal solutions are usually determined in a multi-attribute decision making situation in the absence of uncertainty, where the decision maker has two objectives, and the set of feasible points under consideration must satisfy a given set of constraints. When all the Pareto optimal solutions are graphed in the x-y plane with the x-axis score being the score on the first objective and the y-axis score being the score on the second objective, the graph is called an efficient frontier or a tradeoff curve. Tradeoff curves for Pareto optimal solutions for emissions versus capital and operating cost, as well as primary energy consumption versus costs were calculated using the following procedure (Winston, 1994):

- Step one: choose an objective (e.g. objective 1) and determine the best value of this objective that can be attained (say $z_1$). For the solution attaining $z_1$, find the value of objective 2, $z_2$. Then ($z_1$, $z_2$) is a point on the tradeoff curve.
- Step 2: for the values z of objective 2 that are better than $z_2$, solve the optimization problem in Step 1 with the additional constraint: the value of objective 2 is a least as good as $z$. Varying $z$ (over values of $z$ preferred to $z_2$) will give other points on the tradeoff curve.
- Step 3: in Step 1, we obtained one endpoint of the tradeoff curve. If we determine the best value of objective 2 that can be attained we obtain the other endpoint of the tradeoff curve.

Two alternatives for grid-based systems are considered: electricity obtained from the US average electric generation mix and electricity obtained from a NGCC power plant. Thus, in one set of problems, electricity can be provided by the US average electric grid and/or cogeneration system(s). In another set of problems, electricity can be provided by the NGCC and/or cogeneration system(s). These sets of problems are used to examine the variation in optimization results when considering an efficient grid-based system such as NGCC versus the conventional electric grid.

Two models are developed: the *Hourly LCA Optimization Model* and the *Simplified Yearly Optimization Model*. Hourly energy use of an office building can be used to define the electrical, heating, and cooling parameters in the LCA optimization models. In the *Hourly LCA Optimization Model*, the problems are formulated as 12 individual days by considering hourly energy use in an *average day* in a month, i.e., 12 average days represent the 12 months of the year of operation of the building. In the *Simplified Yearly LCA Optimization Model*, the problems are formulated by considering the total energy use of the building in the *year*, based on hourly energy use data; In this case, one problem represents yearly building operation.

## 4.3 ASSUMPTIONS

The basic assumptions considered in developing the LCA optimization models are as follows:

- The thermal and electric conversion efficiencies and capacities of cogeneration systems are achievable. According to the documented literature, the cogeneration systems can operated at the modeled part load levels with the thermal and electric conversion efficiencies and capacitates specified. This assumption is a simplified approximation of the actual operation of these systems, as more variables like temperature and pressure plays some role in depicting the thermodynamic aspects of operation. The scope of the research does not address improving the efficiencies of these cogeneration systems by studying the effects of varying process parameters, such as voltage, fuel utilization, temperature, and pressure. This assumption fulfils the objective of the research in order to predict the performance of cogeneration systems with specific operation characteristics in building applications.
- MT and SOFC operating characteristics and emissions are based on the literature and their sizes are chosen based on current available units for commercial use.
- ICE cogeneration systems are available in different sizes. A sensitivity analysis was done to determine the performance of ICE when the LCA optimization model was implemented for a commercial office building case study. The results of the sensitivity analysis indicated that units were chosen for operation not only based on their emission and energy consumption characteristics but also because of their efficiency and capacity characteristics[8]. The ICE cogeneration system that was used in the LCA optimization model implementation was selected because it was found to be the most suitable for use because of its operating characteristics, energy use and emissions profile.
- Cogeneration system's operation is not limited to a certain strategy, i.e., electric or thermal load following, but instead the model allows for the flexibility of operating the cogeneration system with the strategy that can result in the best performance. This assumption does not take into consideration the complex policy of electric interconnectivity and time of use which can constrains the optimal operation of the

[8] Sensitivity analyses of ICE sizes are given in Appendix D (section D.2).

cogeneration system. Rapid switching can also lead to increases in maintenance costs and decrease in system's efficiency. This problem can be easily modified to constrain the time of use to investigate the implication of following a particular policy. For the objectives of this research, the current formulation allows for the flexibility of investigating the operation of cogeneration systems as well as utility-based systems with no restrictions on the time of use but rather to identify the operational strategy that can result in best performance according to the defined objectives.

- A MT and ICE cogeneration system can be operated at any time with no penalty for startup and shutdown. The SOFC was modeled to be operated continuously because of its long startup time in practice (startup time is about eight hours). The MT and ICE, on the other hand, have very short startup and shutdown times (the MT can take 2 minutes for startup and 5 minutes for shutdown (Capstone, 2005)). The ICE has similar startup and shutdown times relative to the MT cogeneration system. A sensitivity analysis[9] was done by formulating the optimization model to consider a penalty for startup and shutdown for the MT cogeneration systems. The analysis indicated that when MT cogeneration systems were chosen for operation, they operated for a consecutive period in a day. However, the results from the sensitivity analysis were not significantly different from the results obtained with the formulated optimization model.
- No credit is taken for any electrical or thermal energy generated from the cogeneration systems above the demand. This assumes that no energy storage systems are used and that no assumptions are made about the potential for exporting energy to the locations or uses such as the electric grid or other buildings. This limits the analyses to the building itself. The justification for limiting the analysis to the building can be thought of in a practical way. If cogeneration was broadly implemented, and energy could be exported at low demand, then it might be likely that there would be a surplus at times when most co generators were looking to export.

[9] Sensitivity analysis on modified models with the penalty is given in Appendix D (D.1).

- A study period of ten years was used in evaluating the life cycle capital and operation costs of the cogeneration systems[10], the gas boiler and the NGCC whereas the cost of fuel from the average electric grid was obtained from the literature and national average electric cost data (EIA, 2005b).

## 4.4 HOURLY LCA OPTIMIZATION MODEL FORMULATION

In the first set of problems, the *Hourly LCA Optimization Model* is formulated to consider power supply from the average electric grid and/or a single or multiple cogeneration system(s) (MT, ICE and SOFC) at a particular hour. Thermal energy can be supplied by a gas boiler and/or a single or multiple cogeneration system(s) (MT, ICE and SOFC) at a particular time. In addition, part load operation is also considered in the formulations for modeling the cogeneration systems. The SOFC process can operate between seven output levels, the MT can operate at four part load levels, and the ICE can operate at three part load levels. Also, the formulation allows for the operation of multiple cogeneration systems at a specific time, except for the SOFC where a single unit is modeled. *Ten* microturbine units and *six* internal combustion units are considered in the formulation. Cooling demand can be met by an electric chiller, which can be driven by electricity from the grid or a cogeneration system, and/or by an absorption chiller, which can be driven by heat from a gas boiler or a cogeneration system at a particular time.

In the second set of the problems, the *Hourly LCA Optimization Model* is formulated to consider power supply from the NGCC power plant instead of the US average electric generation power plant. The *Hourly LCA Optimization Model* is used to minimize the potential life cycle emissions, primary energy use, and costs (evaluated in separate problems) that may result from the operation of energy systems in a building to meet the electrical, thermal and cooling demands.

---

[10] Appendix B contains details on cost calculations and assumptions.

The following notation is used in the formulations:

***Energy Use Parameters***

| | |
|---|---|
| *h* | Index number for operating hours, $h$ = 1, 2, ..., 24. |
| $C_h$ | Cooling demand required for space cooling at hour $h$, [*kWh*]. |
| $H_h$ | Heating demand required for space and water heating at hour $h$, [*kWh*]. |
| $P_h$ | Power required for miscellaneous electric demand, other than cooling, at hour $h$, [*kWh*] |

***Cogeneration Systems Parameters:***

| | |
|---|---|
| $MT_p$ | Notation for part load operating level of a MT unit: $MT_p$ = 25%, 50%, 75%, 100%. |
| $ICE_p$ | Notation for part load operating level of an ICE unit: $ICE_p$ = 50%, 75%, 100%. |
| $SOFC_p$ | Notation for part load operating level of a SOFC: $SOFC_p$ = 62%, 68%, 78%, 85%, 93%, 100%, 104%. |
| $MT_u$ | Notation for MT unit numbers: $MT_u$ = 1, 2,..., 10. |
| $ICE_u$ | Notation for ICE unit numbers: $ICE_u$ = 1, 2,..., 6. |
| $MaxCap\ MT_{up}$ | The maximum capacity (electric) for MT unit $u$ operating at part load level $p$, [*kW*]. |
| $MinCap\ MT_{up}$ | The minimum capacity (electric) for MT unit $u$ operating at part load level $p$, [*kW*]. |
| $MaxCap\ ICE_{up}$ | The maximum capacity (electric) for ICE unit $u$ operating at part load level $p$, [*kW*]. |
| $MinCap\ ICE_{up}$ | The minimum capacity (electric) for ICE unit $u$ operating at part load level $p$, [*kW*]. |
| $MaxCap\ SOFC_p$ | The maximum capacity (electric) for the SOFC unit operating at part load level $p$, [*kW*]. |
| $MinCap\ SOFC_p$ | The minimum capacity (electric) for the SOFC unit operating at part load level $p$, [*kW*] |
| $PH\ RATIO\ MT_{up}$ | Power to heat efficiency ratio of MT unit $u$ operating at part load level $p$. |
| $PH\ RATIO\ ICE_{up}$ | Power to heat efficiency ratio of ICE unit $u$ operating at part load level $p$. |
| $PH\ RATIO\ SOFC_p$ | Power to heat efficiency ratio of the SOFC unit operating at part load level $p$. |
| $EF\ MT_p$ | Emission factor (EF) resulting from generating *1-kWh* of electric energy from MT unit operating at part load level $_p$, [*kg/kWh*]. |
| $EF\ ICE_p$ | EF resulting from generating *1-kWh* of electric energy from ICE unit operating at part load level $_p$, [*kg/kWh*]. |
| $EF\ SOFC_p$ | EF resulting from generating *1-kWh* of electric energy from the SOFC operating at part load level $_p$, [*kg/kWh*]. |
| $PEC\ MT_p$ | Primary energy consumption (PEC) resulting from generating *1-kWh* of electric energy from MT unit operating at part load level $_p$, [*kWh/kWh*]. |
| $PEC\ ICE_p$ | PEC resulting from generating *1-kWh* of electric energy from ICE unit operating at part load level $_p$, [*kWh/kWh*]. |
| $PEC\ SOFC_p$ | PEC resulting from generating *1-kWh* of electric energy from the SOFC operating at part load level $_p$, [*kWh/kWh*]. |
| $CF\ MT_p$ | Cost Factor (CF) due to generating *1-kWh* of electric energy from MT unit operating at part load level $_p$, [*$/kWh*]. |
| $CF\ ICE_p$ | CF [*$/kWh*] due to generating *1-kWh* of electric energy from ICE unit operating at part load level $_p$, [*$/kWh*]. |
| $CF\ SOFC_p$ | CF [*$/kWh*] due to generating *1-kWh* of electricity from the SOFC operating at part load level $_p$, [*$/kWh*]. |

***Grid-based Systems Parameters:***

| | |
|---|---|
| *EF GRID* | EF resulting from obtaining *1-kWh* of electricity from the average electric grid, [*kg/kWh*]. |
| *EF NGCC* | EF resulting from obtaining *1-kWh* of electricity from the NGCC, [*kg/kWh*] |
| *PEC GRID* | PEC resulting from obtaining *1-kWh* of electricity from the average electric grid, [*kWh/kWh*]. |
| *PEC NGCC* | PEC resulting from obtaining *1-kWh* of electricity from the NGCC, [*kWh/kWh*]. |
| *CF GRID* | CF due to generating *1-kWh* of electricity from the average electric grid, [*$/kWh*]. |
| *CR NGCC* | CF due to generating *1-kWh* of electricity from the NGCC, [*$/kWh*]. |

***Cooling Systems Parameters:***

| | |
|---|---|
| $AC_{COP}$ | Coefficient of performance (COP) for the absorption chiller (AC) is a ratio relating the cooling output to the energy input. |
| $EC_{COP}$ | COP for the electric chiller (EC) is a ratio relating the cooling output to the energy input. |

***Boiler Parameters:***

| | |
|---|---|
| *EF BOILER* | EF resulting from obtaining *1-kWh* of thermal energy from the gas boiler, [*kg/kWh*]. |
| *PEC BOILER* | PEC resulting from obtaining *1-kWh* of thermal energy from the gas boiler, [*kWh/kWh*]. |
| *CF BOILER* | CF resulting from obtaining *1-kWh* of thermal energy from the gas boiler, [*$/kWh*]. |

***Cogeneration Systems Decision Variables:***

| | |
|---|---|
| $H\ MT_{uph}$ | Heat provided by MT unit *u* operating at part load level *p* at hour *h*, [*kWh*] |
| $P\ MT_{uph}$ | Power provided by MT unit *u* operating at part load level *p* at hour *h*, [*kWh*]. |
| $H\ ICE_{uph}$ | Heat provided by ICE unit *u* operating at part load level *p* at hour *h*, [*kWh*]. |
| $P\ ICE_{uph}$ | Power provided by MT unit *u* operating at part load level *p* at hour *h*, [*kWh*]. |
| $H\ SOFC_{ph}$ | Heat provided by the SOFC unit operating at part load level *p* at hour *h*, [*kWh*]. |
| $P\ SOFC_{ph}$ | Power provided by the SOFC unit operating at part load level *p* at hour *h*, [*kWh*]. |
| $BINARY\ MT_{uph}$ | Binary variable for MT unit *u* operating at part load level *p* at hour *h; a unit is given a value of one if operating at a part load level and a value of zero if not.* $\begin{cases} 1 & \textit{if unit is in use} \\ 0 & \textit{otherwise} \end{cases}$ |
| $BINARY\ ICE_{uph}$ | Binary variable for ICE unit *u* operating at part load level *p* at hour *h; a unit is given a value of one if operating at a part load level and a value of zero if not.* $\begin{cases} 1 & \textit{if unit is in use} \\ 0 & \textit{otherwise} \end{cases}$ |
| $BINARY\ SOFC_{ph}$ | Binary variable for the SOFC unit operating at part load level *p* at hour *h; a unit is given a value of one if operating at a part load level and a value of zero if not.* $\begin{cases} 1 & \textit{if unit is in use} \\ 0 & \textit{otherwise} \end{cases}$ |

***Grid-based Systems Decision Variables:***

| | |
|---|---|
| $P\ GRID_h$ | Power provided by the average electric grid at hour *h*, [*kWh*]. |
| $P\ NGCC_h$ | Power provided by the NGCC at hour *h*, [*kWh*]. |

***Cooling Systems Decision Variables:***

| | |
|---|---|
| $C\_AC_h$ | Cooling provided by the absorption chiller at hour *h*, [*kWh*]. |
| $C\_EC_h$ | Cooling provided by the electric chiller at hour *h* , [*kWh*]. |
| $H\ AC_h$ | Heating required to drive the absorption chiller to supply the cooling demand at hour *h*, [*kWh*] |
| $P\ EC_h$ | Power required to drive the electric chiller to supply the cooling demand at hour *h*, [*kWh*] |

***Boiler Decision Variable:***

| | |
|---|---|
| $H\ B_h$ | Heat provided by the gas boiler at hour *h*, [*kWh*]. |

### 4.4.1 Hourly LCA Optimization Model for Minimum Life Cycle Emissions

#### 4.4.1.1 Electric Utility Option (1): US Average Electric Grid

In the *LCA Hourly Optimization Model*, the objective function, equation [4.1], is formulated to minimize the potential life cycle emissions that may result from operating the energy systems to meet the electrical, heating and cooling demand of a building in the 24 hours of a day. Each of the following indicators is evaluated in a separate problem:

- GWP expressed in [*kg of* $CO_2$ *equivalents*],
- AP expressed in [*kg of* $SO_2$ *equivalents*],
- TOPP expressed in [*kg of TOPP equivalents*],
- $CO_2$ expressed in [*kg*]
- $SO_2$ expressed in [*kg*], and
- $NO_x$ expressed in [*kg*].

The model formulation is as follows:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\ GRID_h \times EF\ GRID\right] + \left[\sum_{u=1}^{10}\sum_{p \in P} P\ MT_{uph} \times EF\ MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p \in P} P\ ICE_{uph} \times EF\ ICE_{up}\right] \\ + \left[\sum_{p \in P} P\ SOFC_{ph} \times EF\ SOFC_p\right] + \left[H\ BOILER_h \times EF\ BOILER\right] \end{array} \right\} \quad [4.1]$$

s.t.

$$\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{uph} + \sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{uph} + \sum_{p \in P} P\ SOFC_{ph} + P\ GRID_h \ge P_h + P\ EC_h \forall h \in H \quad [4.2]$$

$$\sum_{u=1}^{10} \sum_{p \in P} H\ MT_{uph} + \sum_{u=1}^{6} \sum_{p \in P} H\ ICE_{uph} + \sum_{p \in P} H\ SOFC_{ph} + H\ BOILER_h \ge H_h + H\ AC_h \forall h \in H \quad [4.3]$$

$$C\ AC_h + C\ EC_h = C_h \forall h \in H \quad [4.4]$$

$$C\ AC_h = H\ AC_h \times AC_{COP} \forall h \in H \quad [4.5]$$

$$C\ EC_h = P\ EC_h \times EC_{COP} \forall h \in H \quad [4.6]$$

$$P\ MT_{uph} = H\ MT_{uph} \times PH\ RATIO\ MT_{up} \forall h \in H \quad [4.7]$$

$$P\ ICE_{uph} = H\ ICE_{uph} \times PH\ RATIO\ ICE_{up} \forall h \in H \quad [4.8]$$

$$P\ SOFC_{ph} = H\ SOFC_{ph} \times PH\ RATIOSOFC_p \forall h \in H \quad [4.9]$$

$$\begin{array}{l} P\ MT_{uph} \ge MinCap\ MT_{up} \times BINARY\ MT_{uph} \forall h \in H \\ P\ MT_{uph} \le MaxCap\ MT_{up} \times BINARY\ MT_{uph} \forall h \in H \end{array} \quad [4.10]$$

$$\begin{array}{l} P\ ICE_{uph} \ge MinCap\ ICE_{up} \times BINARY\ ICE_{uph} \forall h \in H \\ P\ ICE_{uph} \le MaxCap\ ICE_{up} \times BINARY\ ICE_{uph} \forall h \in H \end{array} \quad [4.11]$$

$$\begin{array}{l} P\ SOFC_{ph} \ge MinCap\ SOFC_p \times BINARY\ SOFC_{ph} \forall h \in H \\ P\ SOFC_{ph} \le MaxCap\ SOFC_p \times BINARY\ SOFC_{ph} \forall h \in H \end{array} \quad [4.12]$$

$$\sum_{p \in P} BINARY\ MT_{uph} \le 1, \forall h \in H, u \in U \quad [4.13]$$

$$\sum_{p \in P} BINARY\ ICE_{uph} \le 1, \forall h \in H, u \in U \quad [4.14]$$

$$\sum_{p \in P} BINARY\ SOFC_{ph} \le 1, \forall h \in H \quad [4.15]$$

$$\sum_{p \in P} P\ MT_{uph} \ge \sum_{p \in P} P\ MT_{u+1ph} \forall h \in H, u < 10 \quad [4.16]$$

$$\sum_{p \in P} P\ ICE_{uph} \ge \sum_{p \in P} P\ ICE_{u+1ph} \forall h \in H, u < 6 \quad [4.17]$$

$$\sum_{p \in P} BINARY\ SOFC_{ph} = \sum_{p \in P} BINARY\ SOFC_{ph-1}, \forall h > 1 \in H \quad [4.18]$$

$$All\,Variables \geq 0 \qquad [4.19]$$

Constraint [4.2] is formulated to ensure that a building's power demand consisting of power required for miscellaneous office equipment and lights, and power required for cooling (with electric chiller) must be satisfied each hour. Each hour, power can be provided by specific cogeneration unit(s) (MT, ICE, SOFC) operating at a particular load and/or the grid (average US electric grid in one set of problems and NGCC power plant in another set of problems).

Constraint [4.3] is formulated to ensure that a building's thermal demand, consisting of thermal energy required for space and water heating, and thermal energy required for cooling (with absorption chiller) must be satisfied each hour. At a particular hour, thermal energy can be provided by a gas boiler and/or specific cogeneration unit(s) (MT, ICE, SOFC) operating at a particular load.

Constraint [4.4] is formulated to ensure that a building's cooling demand must be satisfied each hour. At a particular hour, cooling can be provided by an absorption chiller and/or an electric chiller. The cooling obtained from the absorption chiller depends on the coefficient of performance (COP) of the chiller. Constraint [4.5] relates the amount of cooling obtained from an absorption chiller to the energy input (thermal energy from a gas boiler or a cogeneration system) by the COP of the absorption chiller. Likewise, constraint [4.6] relates the amount of cooling obtained from the electric chiller to the energy input (electric energy from a grid or a cogeneration system) by the COP of the electric chiller.

The electric and thermal energy outputs of a cogeneration system are correlated by the power to heat ratio of that system. The power to heat ratio indicates the ratio of the efficiency of power generation to the efficiency of thermal energy generation from a cogeneration system. Constraints [4.7], [4.8] and [4.9], are formulated to relate the power and thermal output of a cogeneration system, MT, ICE and SOFC, respectively, operating at a particular load at a particular time.

Constraints [4.10], [4.11] and [4.12] are formulated to ensure that at a particular time, the electric energy output from a cogeneration system, MT, ICE and SOFC, respectively, operating at a particular part load level is less than or equal to the maximum capacity and more than or equal to the minimum capacity of that unit operating at that level. These constraints are formulated using the binary variable for each of the cogeneration system, which takes the value of one if in use or zero if not.

Since cogeneration systems can only be operated at a single part load level at a particular time, constraints [4.13], [4.14] and [4.15] are formulated to ensure that at a particular time, only a single part load operating level is in use for MT, ICE and SOFC, respectively. In the formulation multiple units are considered for MT and ICE cogeneration systems; constraints [4.16] and [4.17] are formulated to ensure that units are operated in sequence. For example, MT unit (1) is operated first before unit (2) is in use and so on. In practice SOFC cogeneration systems are operated continuously because of the long start up times required for operation (eight hours for startup time). Constraint [4.18] is formulated to ensure the continuous operation of the SOFC unit.

#### 4.4.1.2 Electric Utility Option (2): NGCC

In the second set of problems the objective function is formulated to consider electricity obtained from the NGCC power plant instead of the US average electric grid. Thus, the "EF Grid" is replaced by "EF NGCC" in the objective function and the decision variable "P GRID" is replaced by "P NGCC" in the objective function, equation [4.1] and constraint [4.2]. All other constraints in the formulation in *Section 4.4.1.1* remain the same and are used in the problem formulation. Thus, the objective function, equation [4.1] and constraint [4.2] in the *Electric Utility Option 1* problem are modified in the NGCC problem formulation as follows:

$$Min \sum_{h=1}^{24} \left\{ \begin{aligned} &\left[P\ NGCC_h \times EF\ NGCC\right] + \left[\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{uph} \times EF\ MT_{up}\right] + \left[\sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{uph} \times EF\ ICE_{up}\right] \\ &+ \left[\sum_{p \in P} P\ SOFC_{ph} \times EF\ SOFC_p\right] + \left[H\ BOILER_h \times EF\ BOILER\right] \end{aligned} \right\} \qquad [4.20]$$

s.t.

$$\sum_{u=1}^{10} \sum\nolimits_{p \in P} P\ MT_{uph} + \sum_{u=1}^{6} \sum\nolimits_{p \in P} P\ ICE_{uph} + \sum\nolimits_{p \in P} P\ SOFC_{ph} + P\ NGCC_h \geq P_h + P\ EC_h \qquad [4.21]$$

and also equations: [4.3] to [4.19]

### 4.4.2 Hourly LCA Optimization Model for Minimum Life Cycle Primary Energy Consumption

Two sets of problems using the *Hourly LCA Optimization Model* are formulated to minimize the potential life cycle primary energy consumption that may result from operating the energy systems to meet the electrical, heating and cooling demand of a building in the 24 hours of a day.

#### 4.4.2.1 Electric Utility Option (1): US Average Electric Grid

The first set of problems is formulated to consider the US average electric grid, cogeneration systems, the gas boiler, and absorption and electric chillers. For this problem set, the same constraints for minimizing emissions problem, equations [4.2] to [4.19], are used in the formulation. In the objective function, equation [4.1], the emission factors (EF) associated with the energy systems are replaced by primary energy consumption factors (PEC) for each of the system. The objective function becomes:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\ GRID_h \times PEC\ GRID\right] + \left[\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{uph} \times PEC\ MT_{up}\right] + \left[\sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{uph} \times PEC\ ICE_{up}\right] \\ + \left[\sum_{p \in P} P\ SOFC_{ph} \times PEC\ SOFC_p\right] + \left[H\ BOILER_h \times PEC\ BOILER\right] \end{array} \right\} \qquad [4.22]$$

s.t. equations [4.2] to [4.19]

#### 4.4.2.2 Electric Utility Option (2): NGCC

The second set of problems is formulated to consider the NGCC instead of the US average grid, cogeneration systems, the gas boiler, and absorption and electric chillers. In the second set, the same constraints for the minimizing emissions problem, equations [4.2] to [4.19], are used in the formulation, except that equation [4.2] becomes equation [4.21]. The objective function becomes:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\ NGCC_h \times PEC\ NGCC\right] + \left[\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{uph} \times PEC\ MT_{up}\right] + \left[\sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{uph} \times PEC\ ICE_{up}\right] \\ + \left[\sum_{p \in P} P\ SOFC_{ph} \times PEC\ SOFC_p\right] + \left[H\ BOILER_h \times PEC\ BOILER\right] \end{array} \right\} \qquad [4.23]$$

s.t. equations [4.21] and [4.3] to [4.19]

### 4.4.3 Hourly LCA Optimization Model for Minimum Life Cycle Cost

Two sets of the *Hourly LCA Optimization Model* are formulated to minimize the capital and operating costs that may result from operating the energy systems to meet the electrical, heating and cooling demand of a building in the 24 hours of a day.

#### 4.4.3.1 Electric Utility Option (1): US Average Electric Grid

The first set of problems is formulated to consider the US average electric grid, cogeneration systems the gas boiler, and absorption and electric chillers. For this problem set, the same constraints for minimizing emissions problem, equations [4.2] to [4.19], are used in the formulation. In the objective function, equation [4.1], the emission factors (EF) associated with the energy systems are replaced by cost factors (CF) for each of the system. The objective function becomes:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\ GRID_h \times CF\ GRID\right] + \left[\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{uph} \times CF\ MT_{up}\right] + \left[\sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{uph} \times CF\ ICE_{up}\right] \\ + \left[\sum_{p \in P} P\ SOFC_{ph} \times CF\ SOFC_p\right] + \left[H\ BOILER_h \times CF\ BOILER\right] \end{array} \right\} \qquad [4.25]$$

s.t. equations [4.2] to [4.19].

#### 4.4.3.2 Electric Utility Option (2): NGCC

The second set of problems is formulated to consider the NGCC instead of the US average grid, cogeneration systems, the gas boiler, and absorption and electric chillers. In the second set, the same constraints for the minimizing emissions problem, equations [4.2] to [4.19], are used in the formulation, except that equation [4.2] becomes equation [4.21]. The objective function becomes:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\ NGCC_h \times CF\ NGCC\right] + \left[\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{uph} \times CF\ MT_{up}\right] + \left[\sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{uph} \times CF\ ICE_{up}\right] \\ + \left[\sum_{p \in P} P\ SOFC_{ph} \times CF\ SOFC_p\right] + \left[H\ BOILER_h \times CF\ BOILER\right] \end{array} \right\} \qquad [4.26]$$

s.t. equations [4.21] and [4.3] to [4.19]

## 4.5 SIMPLIFIED YEARLY LCA OPTIMIZATION MODEL FORMULATION

Similar to the *Hourly LCA Optimization Model*, the *Simplified LCA Optimization Model* is formulated to consider grid-based energy systems, cogeneration systems, the gas boiler and the absorption and electric chillers. The difference in the formulation is that instead of considering the 24 hours of the day, the simplified LCA optimization model objective function is formulated to minimize the impacts over the whole year. The year is represented by six average days and the 24 hours of the day are grouped into five periods. The model allows for optimizing the building operation based on representative data of the whole year, which can be used for design decision making and short term analysis for predicting the performance of the operational strategies. Each of the following indicators is evaluated in a separate problem:

- GWP expressed in [*kg of* $CO_2$ *equivalents*],
- AP expressed in [*kg of* $SO_2$ *equivalents*],
- TOPP expressed in [*kg of TOPP equivalents*],
- $CO_2$ expressed in [*kg*]
- $SO_2$ expressed in [*kg*], and
- $NO_x$ expressed in [*kg*].

The following notation is used in the formulations:

***Energy Use Parameters***

| | |
|---|---|
| $i$ | Index number for the hour periods in the day, $i$ = 1, 2, ..., 5, where<br>$i$ = 1: represents the period consisting of the average of hours 1-7, which are non-working hours of the day;<br>$i$ = 2: represents hour 8, which is a transition hour from non-working hours to the working hours of the day;<br>$i$ = 3: represents the period consisting of the average of hours 9-17, which are the working hours of the day;<br>$i$ = 4: represents hour 18, which is a transition hour from working hours to non-working hours of the day; and<br>$i$ = 5: represents the period consisting of the average of hours 19-24, which are non-working hours of the day; |
| $m$ | Index number for the groups of days in a month, where<br>$m$ = 1: represents a day for the average days in January, February and December;<br>$m$ = 2: represents a day for the average days in March and November;<br>$m$ = 3: represents a day for the average days in April and October;<br>$m$ = 4: represents an average day in May;<br>$m$ = 5: represents a day for the average days in June and September; and<br>$m$ = 6: represents a day for the average days in July and August. |
| $WI_i$ | Weight factor that is multiplied by the number of hours for each interval $_i$, where,<br>$WI_{i=1} = 7$,<br>$WI_{i=2} = 1$,<br>$WI_{i=3} = 9$,<br>$WI_{i=4} = 1$, and<br>$WI_{i=5} = 6$. |
| $WM_m$ | Weight factor that is multiplied by the number of days for each month $_m$, where,<br>$WM_{m=1} = 90$,<br>$WM_{m=2} = 61$,<br>$WM_{m=3} = 61$,<br>$WM_{m=4} = 31$,<br>$WM_{m=5} = 60$,<br>$WM_{m=6} = 62$, |
| $C_{im}$ | Cooling demand required for space cooling at interval $i$ and average days $m$, [$kWh$]. |
| $H_{im}$ | Heating demand required for space and water heating at interval $i$ and average days $m$, [$kWh$]. |
| $P_{im}$ | Power required for miscellaneous electric demand, other than cooling, at interval $i$ and average days $m$, [$kWh$] |

***Cogeneration Systems Decision Variables:***

| | |
|---|---|
| $H\ MT_{upim}$ | Heat provided by MT unit $u$ operating at part load level $p$ at interval $i$ and average days $m$, [$kWh$] |
| $P\ MT_{upim}$ | Power provided by MT unit $u$ operating at part load level $p$ at interval $i$ and average days $m$, [$kWh$]. |
| $H\ ICE_{upim}$ | Heat provided by ICE unit $u$ operating at part load level $p$ at interval $i$ and average days $m$, [$kWh$]. |
| $P\ ICE_{upim}$ | Power provided by MT unit $u$ operating at part load level $p$ at interval $i$ and average days $m$, [$kWh$]. |
| $H\ SOFC_{pim}$ | Heat provided by the SOFC unit operating at part load level $p$ at interval $i$ and average days $m$, [$kWh$]. |
| $P\ SOFC_{pim}$ | Power provided by the SOFC unit operating at part load level $p$ at interval $i$ and average days $m$, [$kWh$]. |
| $BINARY\ MT_{upim}$ | Binary variable for MT unit $u$ operating at part load level $p$ at interval $i$ and average days *; a unit is given a value of one if operating at a part load level and a value of zero if not.* $\begin{cases} 1 & \textit{if unit is in use} \\ 0 & \textit{otherwise} \end{cases}$ |
| $BINARY\ ICE_{upim}$ | Binary variable for ICE unit $u$ operating at part load level $p$ at interval $i$ and average days $m$*; a unit is given a value of one if operating at a part load level and a value of zero if not.* $\begin{cases} 1 & \textit{if unit is in use} \\ 0 & \textit{otherwise} \end{cases}$ |
| $BINARY\ SOFC_{pim}$ | Binary variable for the SOFC operating at part load level $p$ at interval $i$ and average days $m$*; a unit is given a value of one if operating at a part load level and a value of zero if not.* $\begin{cases} 1 & \textit{if unit is in use} \\ 0 & \textit{otherwise} \end{cases}$ |

***Grid-based Systems Decision Variables:***

| | |
|---|---|
| $P\ GRID_{im}$ | Power provided by the average electric grid at interval $i$ and average days $m$, [$kWh$]. |
| $P\ NGCC_{im}$ | Power provided by the NGCC at interval $i$ and average days $m$, [$kWh$]. |

***Cooling Systems Decision Variables:***

| | |
|---|---|
| $C\_AC_{im}$ | Cooling provided by the absorption chiller at interval $i$ and average days $m$, [$kWh$]. |
| $C\_EC_{im}$ | Cooling provided by the electric chiller at interval $i$ and average days $m$, [$kWh$]. |
| $H\ AC_{im}$ | Heating required to drive the absorption chiller to supply the cooling demand at interval $i$ and average days $m$, [$kWh$] |
| $P\ EC_{im}$ | Power required to drive the electric chiller to supply the cooling demand at interval $i$ and average days $m$, [$kWh$] |

***Boiler Decision Variable:***

| | |
|---|---|
| $H\ B_{im}$ | Heat provided by the gas boiler at interval $i$ and average days $m$, [$kWh$]. |

***Note: Cogeneration Systems, Utility Systems, Cooling Systems and Gas Boiler Parameters have the same notation as those defined for the Hourly LCA Optimization Model in Section 4.4.***

### 4.5.1 Simplified Yearly LCA Optimization Model for Minimum Life Cycle Emissions

Two sets of problems considering the two alternatives of electric utility systems: the average electric grid and the NGCC power are formulated using the *Simplified Yearly LCA Optimization Model* to minimize the potential life cycle emissions resulting from a building's operation.

#### 4.5.1.1 Electric Utility Option (1): US Average Electric Grid

The model formulation for minimizing the potential life cycle emissions for the average electric grid utility option is as follows:

$$Min \sum_{m=1}^{6}\sum_{i=1}^{5} WM_m \bullet WI_i \left\{ \begin{array}{l} \left[P\,GRID_{im} \times EF\,GRID\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} P\,MT_{upim} \times EF\,MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} P\,ICE_{upim} \times EF\,ICE_{up}\right] \\ + \left[\sum_{p\in P} P\,SOFC_{pim} \times EF\,SOFC_p\right] + \left[H\,BOILER_{im} \times EF\,BOILER\right] \end{array} \right\} \quad [4.27]$$

s.t.

$$\sum_{u=1}^{10}\sum\nolimits_{p\in P} P\,MT_{upim} + \sum_{u=1}^{6}\sum\nolimits_{p\in P} P\,ICE_{upim} + \sum\nolimits_{p\in P} P\,SOFC_{pim} + P\,GRID_{im} \geq P_{im} + P\,EC_{im} \;\forall\, i \in I, m \in M \quad [4.28]$$

$$\sum_{u=1}^{10}\sum\nolimits_{p\in P} H\,MT_{upim} + \sum_{u=1}^{6}\sum\nolimits_{p\in P} H\,ICE_{upim} + \sum\nolimits_{p\in P} H\,SOFC_{pim} + H\,BOILER_{im} \geq H_{im} + H\,AC_{im} \;\forall\, i \in I, m \in M \quad [4.29]$$

$$C\,AC_{im} + C\,EC_{im} = C_{im} \;\forall\, i \in I, m \in M \quad [4.30]$$

$$C\,AC_{im} = H\,AC_{im} \times AC_{COP} \;\forall\, i \in I, m \in M \quad [4.31]$$

$$C\,EC_{im} = P\,EC_{im} \times EC_{COP} \;\forall\, i \in I, m \in M \quad [4.32]$$

$$P\,MT_{upim} = H\,MT_{upim} \times PH\,RATIO\,MT_{up} \;\forall\, i \in I, m \in M \quad [4.33]$$

$$P\,ICE_{upim} = H\,ICE_{upim} \times PH\,RATIO\,ICE_{up} \;\forall\, i \in I, m \in M \quad [4.34]$$

$$P\,SOFC_{pim} = H\,SOFC_{pim} \times PH\,RATIOSOFC_p \;\forall i \in I, m \in M \quad [4.35]$$

$$\begin{array}{l} P\,MT_{upim} \geq MinCap\,MT_{up} \times BINARY\,MT_{upim} \;\forall\, i \in I, m \in M \\ P\,MT_{upim} \leq MaxCap\,MT_{up} \times BINARY\,MT_{upim} \;\forall\, i \in I, m \in M \end{array} \quad [4.36]$$

$$\begin{array}{l} P\,ICE_{upim} \geq MinCap\,ICE_{up} \times BINARY\,ICE_{upim} \;\forall\, i \in I, m \in M \\ P\,ICE_{upim} \leq MaxCap\,ICE_{up} \times BINARY\,ICE_{upim} \;\forall\, i \in I, m \in M \end{array} \quad [4.37]$$

$$\begin{array}{l} P\,SOFC_{pim} \geq MinCap\,SOFC_p \times BINARY\,SOFC_{pim} \;\forall\, i \in I, m \in M \\ P\,SOFC_{pim} \leq MaxCap\,SOFC_p \times BINARY\,SOFC_{pim} \;\forall\, i \in I, m \in M \end{array} \quad [4.38]$$

$$\sum_{p\in P} P\ MT_{upim} \geq \sum_{p\in P} P\ MT_{u+1pim}\ \forall\, i \in I, m \in M\ \ u < 10 \qquad [4.39]$$

$$\sum_{p\in P} P\ ICE_{upim} \geq \sum_{p\in P} P\ ICE_{u+1pim}\ \forall\, i \in I, m \in M\ \ u < 6 \qquad [4.40]$$

$$\sum_{p\in P} BINARY\ MT_{upim} \leq 1, \forall\, i \in I, m \in M,\ u \in U \qquad [4.41]$$

$$\sum_{p\in P} BINARY\ ICE_{upim} \leq 1, \forall\, i \in I, m \in M, u \in U \qquad [4.42]$$

$$\sum_{p\in P} BINARY\ SOFC_{pim} \leq 1, \forall\, i \in I, m \in M \qquad [4.43]$$

$$\sum_{p\in P} BINARY\ SOFC_{pim} = \sum_{p\in P} BINARY\ SOFC_{pim-1}, \forall\, i > 1 \in I, m \in M \qquad [4.44]$$

$$All\,Variables \geq 0 \qquad [4.45]$$

#### 4.5.1.2 Electric Utility Option (2): NGCC

The formulation for the *Simplified Yearly LCA Optimization Model* with the NGCC utility option is as follows:

$$Min \sum_{m=1}^{6}\sum_{i=1}^{5} WM_m \bullet WI_i \left\{ \begin{array}{l} \left[P\ NGCC_{im} \times EF\ NGCC\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} P\ MT_{upim} \times EF\ MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} P\ ICE_{upim} \times EF\ ICE_{up}\right] \\ + \left[\sum_{p\in P} P\ SOFC_{pim} \times EF\ SOFC_p\right] + \left[H\ BOILER_{im} \times EF\ BOILER\right] \end{array} \right\} \qquad [4.46]$$

s.t.

$$\sum_{u=1}^{10}\sum_{p\in P} P\ MT_{upim} + \sum_{u=1}^{6}\sum_{p\in P} P\ ICE_{upim} + \sum_{p\in P} P\ SOFC_{pim} + P\ NGCC_{im} \geq P_{im} + P\ EC_{im} \forall i \in I, m \in M \qquad [4.47]$$

and also equations [4.29] to [4.45]

### 4.5.2 Simplified Yearly LCA Optimization Model for Minimum Life Cycle Primary Energy Consumption

The *Simplified Yearly LCA Optimization Model* is formulated to solve the potential life cycle primary energy consumptions for each of the utility options: the average electric grid and NGCC.

#### 4.5.2.1 Electric Utility Option (1): US Average Electric Grid

The problem formulation considering the US average electric grid utility option for minimum primary energy consumption is as follows:

$$Min \sum_{m=1}^{6}\sum_{i=1}^{5} WM_m \bullet WI_i \left\{ \begin{array}{l} \left[P\,GRID_{im} \times PEC\,GRID\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} P\,MT_{upim} \times PEC\,MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} P\,ICE_{upim} \times PEC\,ICE_{up}\right] \\ + \left[\sum_{p\in P} P\,SOFC_{pim} \times PEC\,SOFC_{p}\right] + \left[H\,BOILER_{im} \times PEC\,BOILER\right] \end{array} \right\} \quad [4.48]$$

s.t. equations [4.28] to [4.45]

#### 4.5.2.2 Electric Utility Option (2): NGCC

The objective function considering utility option from the NGCC is as follows:

$$Min \sum_{m=1}^{6}\sum_{i=1}^{5} WM_m \bullet WI_i \left\{ \begin{array}{l} \left[P\,NGCC_{im} \times PEC\,NGCC\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} P\,MT_{upim} \times PEC\,MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} P\,ICE_{upim} \times PEC\,ICE_{up}\right] \\ + \left[\sum_{p\in P} P\,SOFC_{pim} \times PEC\,SOFC_{p}\right] + \left[H\,BOILER_{im} \times PEC\,BOILER\right] \end{array} \right\} \quad [4.49]$$

s.t. equations [4.47] and [4.29] to [4.45]

### 4.5.3 Simplified Yearly LCA Optimization Model for Minimum Life Cycle Cost

The following models represent the two utility options which are formulated to minimize the life cycle cost resulting from building operation.

#### 4.5.3.1 Electric Utility Option (1): US Average Electric Grid

The problem formulation for minimizing cost for the US average electric grid utility option is as follows:

$$Min \sum_{m=1}^{6}\sum_{i=1}^{5} WM_m \bullet WI_i \left\{ \begin{array}{l} \left[P\,GRID_{im} \times CF\,GRID\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} P\,MT_{upim} \times CF\,MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} P\,ICE_{upim} \times CF\,ICE_{up}\right] \\ + \left[\sum_{p\in P} P\,SOFC_{pim} \times CF\,SOFC_{p}\right] + \left[H\,BOILER_{im} \times CF\,BOILER\right] \end{array} \right\} \quad [4.50]$$

s.t. equations [4.28] to [4.45]

### 4.5.3.2 Electric Utility Option (2): NGCC

The problem formulation for minimizing cost for the NGCC utility option is as follows:

$$Min \sum_{m=1}^{6} \sum_{i=1}^{5} WM_m \bullet WI_i \left\{ \begin{aligned} &\left[P\ NGCC_{im} \times CF\ NGCC\right] + \left[\sum_{u=1}^{10} \sum_{p \in P} P\ MT_{upim} \times CF\ MT_{up}\right] + \left[\sum_{u=1}^{6} \sum_{p \in P} P\ ICE_{upim} \times CF\ ICE_{up}\right] \\ &+ \left[\sum_{p \in P} P\ SOFC_{pim} \times CF\ SOFC_p\right] + \left[H\ BOILER_{im} \times CF\ BOILER\right] \end{aligned} \right\} \quad [4.51]$$

s.t. equations [4.47] and [4.29] to [4.45]

# 5.0 HYPOTHETICAL CASE STUDY

## 5.1 BUILDING DESCRIPTION & ENERGY SIMULATION

The hypothetical case study is a commercial office building modeled to present average commercial office building characteristics in the USA. Design characteristics for the case building are based on USA average construction obtained from the literature (Sezgen *et al.*, 1995). Energy simulation is used to simulate the commercial office building in order to generate its energy use profile. There are a number of energy simulation software packages available that can be used to generate the electrical and thermal demand profiles of buildings. Energy-10 (SBIC, 1996) is used to simulate the office building and obtain the hourly heating, cooling, and electrical loads.

Energy simulation allows the user to define a number of building characteristics including the principal attributes of the building, such as location with specific weather characteristics, building's size, building-use with specific occupancy characteristics, equipment use schedules, lighting use schedules, etc. Energy simulation software is then used to generate the building hourly energy use profile that matches these building's characteristics. In addition, energy-efficient strategies can be defined, such as day-lighting with associated dimming of artificial lights, using energy-efficient lights, improving insulation throughout, improving windows, reducing infiltration, incorporating passive solar heating, shading windows, adding thermal mass, installing higher efficiency HVAC systems, relocating ducts to inside the thermal envelope, enhancing HVAC controls, and using an economizer cycle (SBIC, 1996).

In order to simulating the building's operation, the energy simulation software executes hour-by-hour thermal and electrical performance calculations based on hourly weather data for the site, in addition to the building description and operation characteristics. The site location for the office building is chosen in Columbia, Missouri. Table 5-1 shows the characteristics of the location and Table 5-2 shows the weather characteristics of the location. The building characteristics are given in Table 5-3.

**Table 5-1: Building's location characteristics.**

| Building Location Characteristics | |
|---|---|
| Latitude: | 38.8 |
| Longitude: | 92.2 |
| Elevation: | 887 ft |
| Design Day Dry Bulb (Winter 99.0%): | -1.0 °F |
| Design Day Dry Bulb (Winter 97.5%): | 4.0 °F |
| Design Day Dry Bulb (Summer 2.5%): | 94.0 °F |
| Design Day Wet Bulb (Summer 2.5%): | 74.0 °F |

**Table 5-2: Building's location weather characteristics.**

| Month | TAA | TMXA | TMNA | TMX | TMN | TWBA | RH | WSA | HS | HDD | CDD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 26.4 | 35.1 | 18.8 | 60 | 3 | 23.3 | 65.7 | 10.7 | 704 | 1179 | 0 |
| February | 31.9 | 41.5 | 21.8 | 63 | 0 | 28.5 | 68.3 | 12.1 | 1027 | 935 | 0 |
| March | 43.2 | 54.5 | 32.7 | 81 | 11 | 38 | 65.6 | 12.5 | 1309 | 670 | 6 |
| April | 56.4 | 67.5 | 45 | 81 | 29 | 47.8 | 56.2 | 12.6 | 1729 | 269 | 7 |
| May | 64.8 | 74.3 | 54.3 | 87 | 37 | 56.9 | 64.1 | 7.7 | 1886 | 95 | 74 |
| June | 71.9 | 81.7 | 62.5 | 89 | 51 | 64.6 | 69.6 | 9.6 | 2142 | 8 | 221 |
| July | 78.1 | 89.8 | 67.2 | 100 | 57 | 69 | 67.1 | 9 | 2047 | 4 | 422 |
| August | 75.6 | 87.7 | 65.2 | 100 | 56 | 68 | 71.1 | 7.4 | 1896 | 0 | 356 |
| September | 68.4 | 78.4 | 58.8 | 87 | 45 | 61.6 | 70.8 | 8.8 | 1495 | 29 | 136 |
| October | 56.1 | 67.9 | 45.5 | 81 | 31 | 50.1 | 67.8 | 9.3 | 1172 | 265 | 8 |
| November | 42.1 | 50.7 | 34.8 | 73 | 23 | 38.3 | 72.1 | 9.3 | 723 | 668 | 0 |
| December | 32.1 | 41 | 23.9 | 66 | 0 | 28.9 | 70.8 | 12 | 593 | 1009 | 0 |
| Year | 53.9 | 64.2 | 44.2 | 100 | 0 | 47.9 | 67.4 | 10.1 | 1394 | 5129 | 1228 |

TAA Average Dry Bulb Temperature, °F
TMXA Average Daily Maximum Dry Bulb Temperature, °F
TMNA Average Daily Minimum Dry Bulb Temperature, °F
TMX Maximum Dry Bulb Temperature, °F
TMN Minimum Dry Bulb Temperature, °F
TWBA Average Wet Bulb Temperature, °F
WSA Average Wind Speed, MPH
HS Average Daily Horizontal Solar Radiation, Btu/ft²
RH Relative Humidity, %
HDD Heating Degree Days, Base 65.0 °F
CDD Cooling Degree Days, Base 65.0 °F

**Table 5-3: Building's construction characteristics.**

| **Case Building's Attributes** | |
|---|---|
| Location | Columbia (Missouri) |
| Floor Area, ft² | 100,000 |
| Surface Area, ft² | 74443 |
| Volume, ft³ | 1300000 |
| Surface Area Ratio | 1.04 |
| Total Conduction UA, Btu/h-F | 20033.5 |
| Average U-value, Btu/hr-ft²-F | 0.269 |
| Wall Construction | 8-in Brick/Foam, rigid insulation and gypsum board, R = 20.0 |
| Roof Construction | Flat, built-up roofing, rigid insulation and gypsum board ceiling, r-19, R = 10.9 |
| Floor type, Insulation | Slab on Grade, Ref f= 25.1 |
| Window Construction | Double glazed with aluminum frames , U = 0.7 |
| Wall total gross area, ft² | 41110 |
| Roof total gross area, ft² | 16667 |
| Ground total gross area, ft² | 16667 |
| Window (N/E/S/W: Roof) | 304/202/304/202:0 |
| Window total gross area, ft² | 24288 |
| Glazing | Double, U = 0.49 |

### 5.1.1 Average Day Energy Use

The hourly energy use profile for the simulated commercial office building consists of:

- hourly *electrical load*, which is the electrical demand required for office equipment and lights only with no cooling included,
- hourly *cooling load*, is the cooling demand required for space cooling (chiller efficiencies are not included), and
- hourly *heating load*, which is the heating demand required for space and water heating.

The energy use profile for the building is obtained for 365 days of a year. The data is then analyzed and hourly energy use for average days representing each month of the year are obtained. Thus, hourly electrical, cooling and heating loads for 12 average days representing each month in the year are generated. Figure 5-1 shows the hourly *electrical load* of the 12 average days and Figure 5-2 shows the total power demand in an average day in the 12 months, respectively. The electric load profile follows uniform characteristics throughout the year for the 24 hours of the day: the electric load is least during the non-working hours (hours 1-7 and hours 19-24) and peaks during the working hours of the day (hours 8-18). Since the electric load consists of primarily office equipment and lighting, the electric load throughout the year is almost constant and small variations between the months are due to the operation of the fan used in the ventilation system.

Figure 5-3 shows the hourly *cooling load* of the 12 average days and Figure 5-4 shows the total cooling demand in an average in the 12 months, respectively. The cooling load profile also follows uniform characteristics throughout the 24 hours of the day: the cooling load is least during the non-working hours (hours 1-7 and hours 19-24) and peaks during the working hours of the day (hours 8-18). Unlike the electric load of the building, the cooling load varies throughout the year. The average days in January, February and December have the lowest cooling load. The cooling load starts to increase during the days in March and November, followed by the days in April and October, the day in May, the days of June and September and, finally, the highest cooling demand occurs during the days in July and August.

Figure 5-5 shows the hourly *heating load* of the 12 average days and Figure 5-6 shows the 12 heating demands in an average day in the 12 months, respectively. The heating load profile has the opposite characteristics of the electrical and heating load profiles. During the 24 hours of the day, the heating load of the building is the least during working hours of the day (hours 8-18) and is the highest during the non-working hours (hours 1-7 and 19-14). The heating load varies throughout the year. The days in January, February and December have the highest heating load. The heating load then decreases during the average days in March and November, followed by the days in April and October, the day in May, the days in June and September, and, finally, the lowest heating demand occurs during the days in July and August.

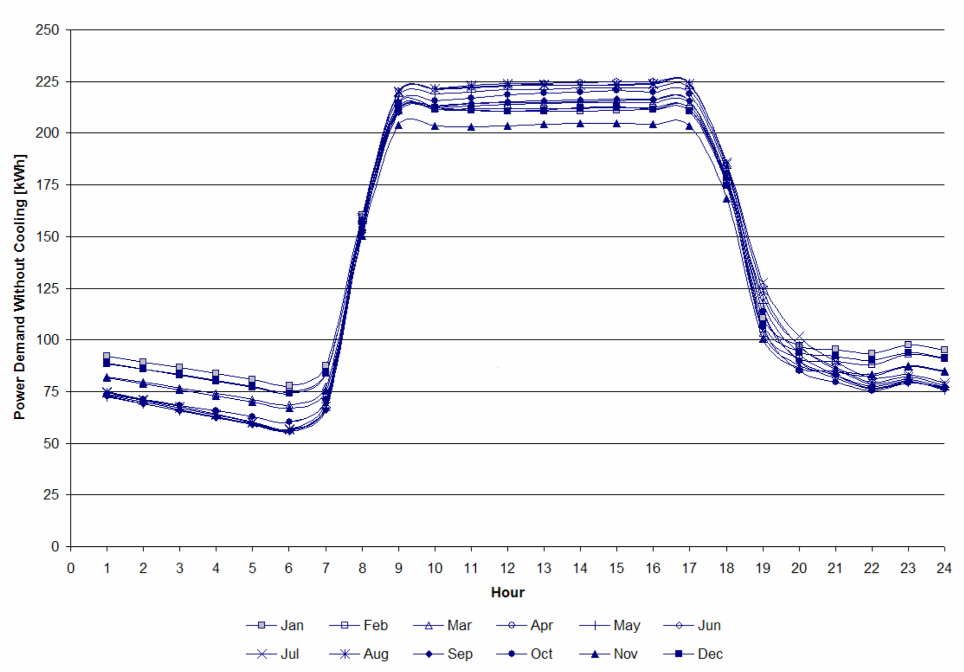



**Figure 5-1: Hourly power demand (without cooling) of the building for 12 days in 12 months.**

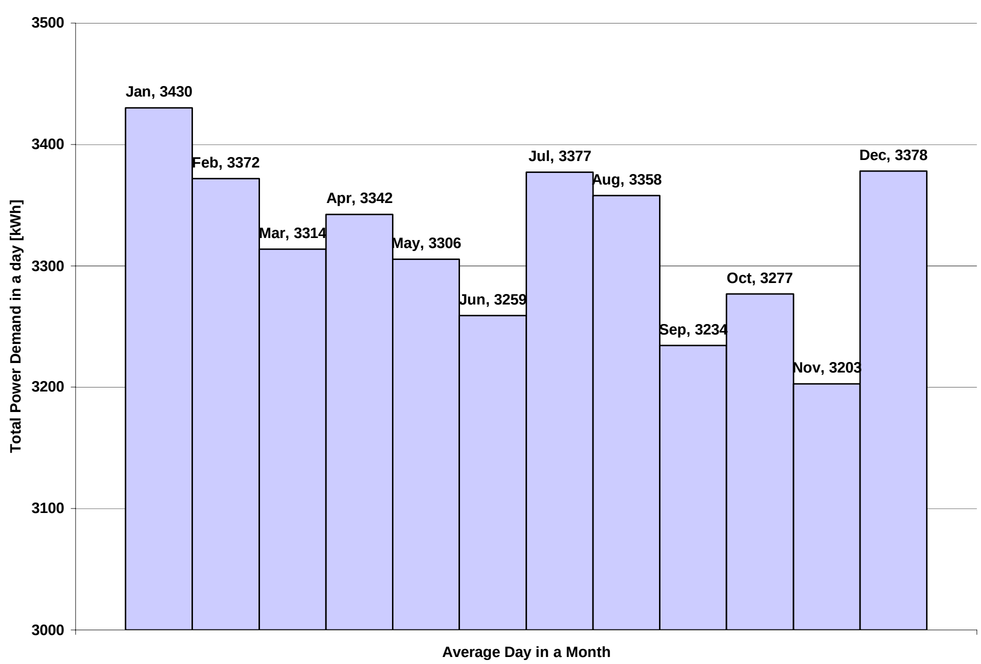



**Figure 5-2: Total power demand (without cooling) in 12 days of the 12 months.**

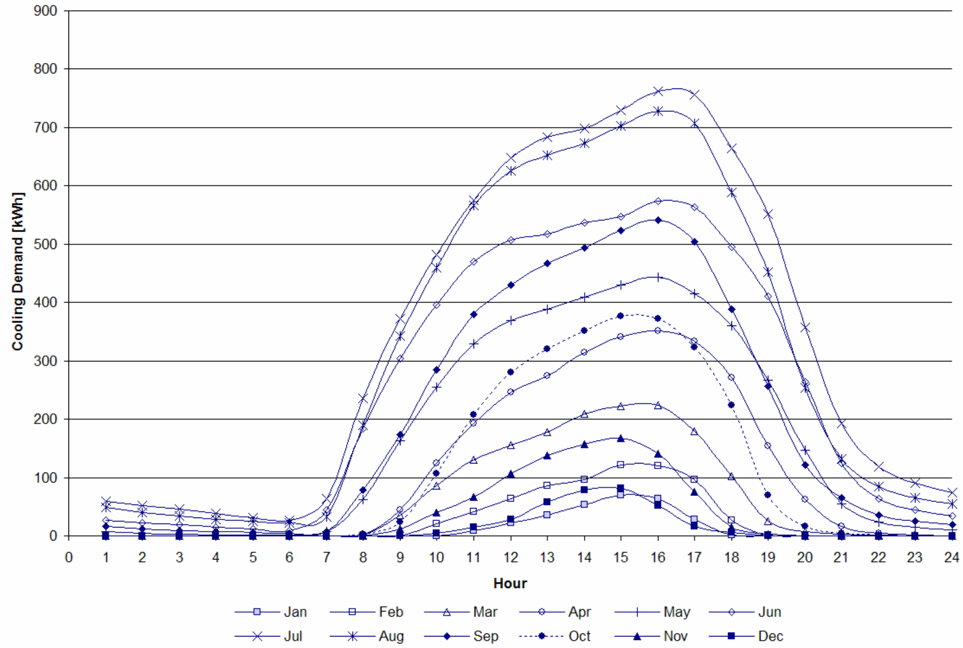



**Figure 5-3: Hourly cooling demand of the building for 12 days of the 12 months.**

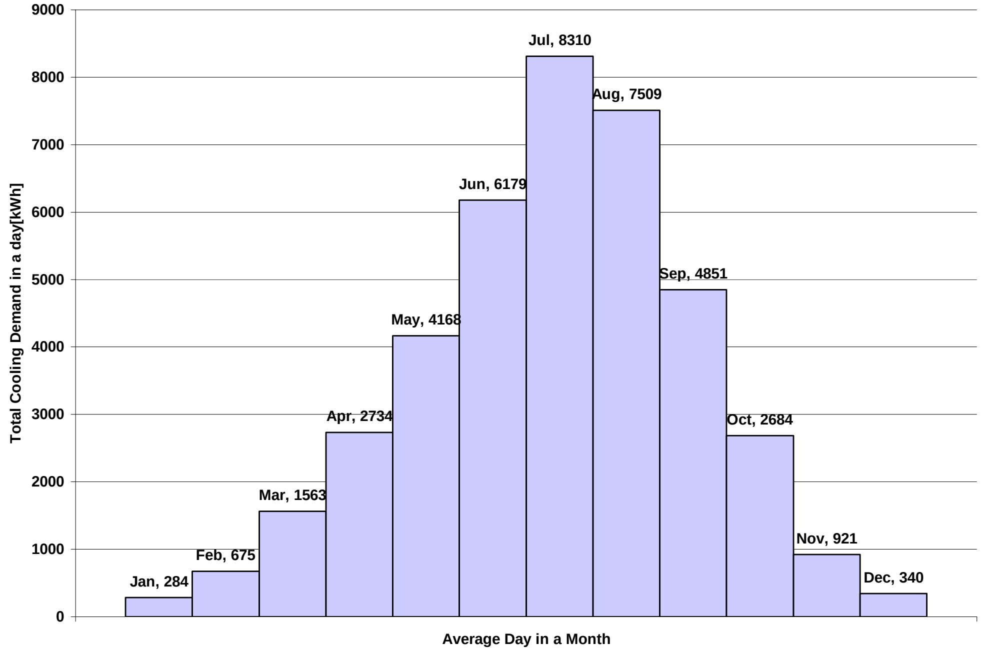



**Figure 5-4: Total cooling demand in 12 days of the 12 months.**

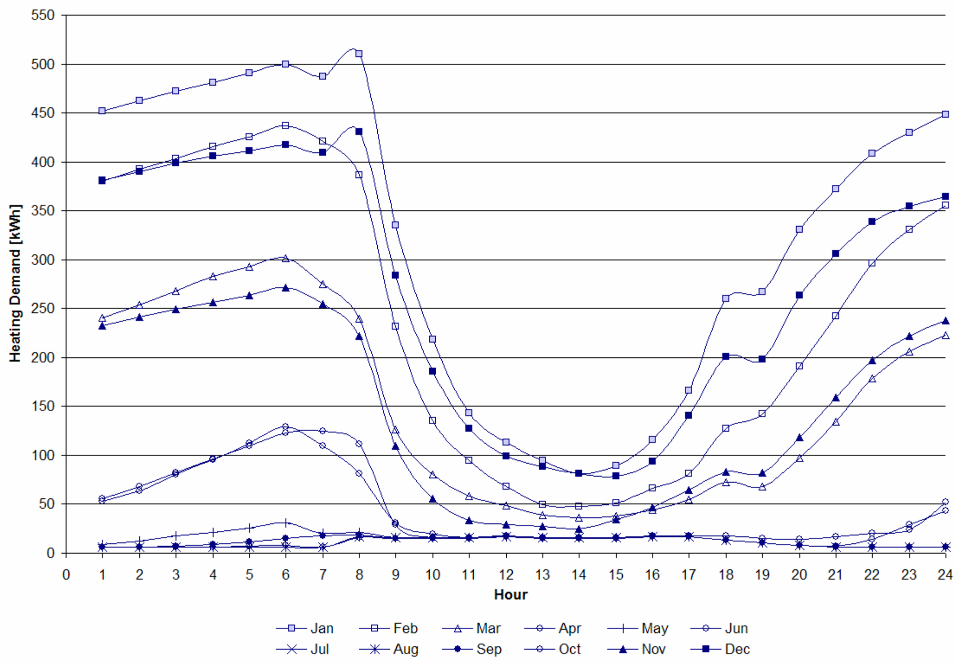



**Figure 5-5: Hourly heating demand for 12 days of the 12 months.**

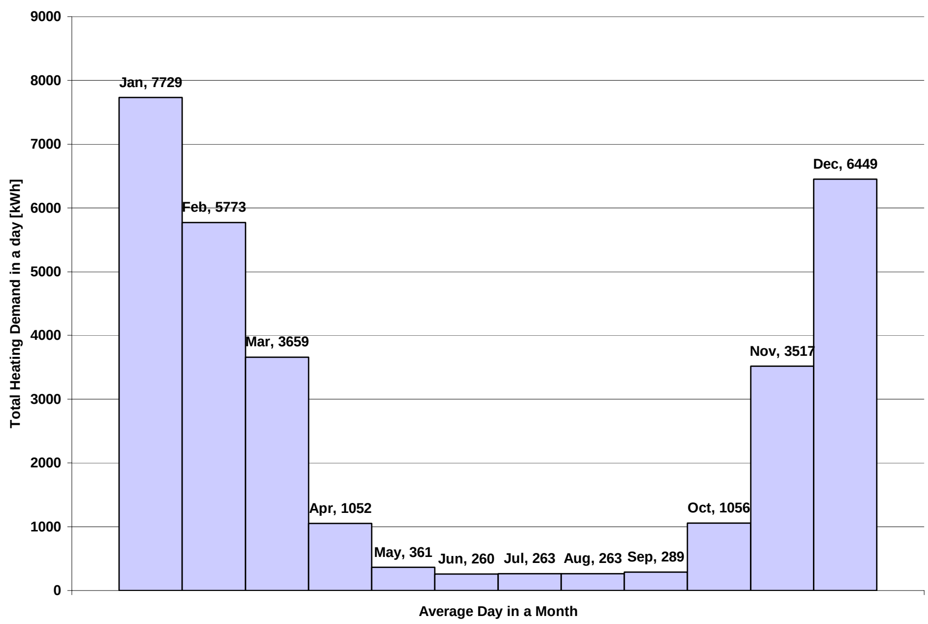



**Figure 5-6: Total heating demand in 12 days of the 12 months.**

### 5.1.2 Periodical Energy Use

The hypothetical office building energy use was further simplified to aggregate the energy use into periods that had similar characteristics. The 12 average days, representing the 12 months in the in the year, were aggregated into *six* groups. This grouping was based on the analysis of the energy use profile (electrical, cooling and heating) of the building. The values for each group of average day energy use categories (electrical, cooling and heating) were obtained provided that all values for each group lies within ± 5% of the mean value. The yearly energy use of the building was grouped as follows:

- *Group 1*: the average days in January, February and December are averaged into a single day representing a day in a heating month in the year.
- *Group 2*: the average days in March and November are averaged into a single day representing a day in a mild heating month in the year (with different loads than *Group 1*).
- *Group 3*: the average days in April and October are averaged into a single day representing a mild day in the year.
- *Group 4*: this group consists of the average day in May, which represents a transition month between heating and cooling months in the year.
- Group 5: the average days in June and September are averaged into a single day representing a mild cooling month in the year.
- Group 6: the average days in July and August are average into a single day representing a significant cooling month in the year (with different loads than *Group 5*).

Furthermore, since the energy use profile of the office building follows uniform characteristics during the day, the 24 hour energy use of the building are aggregated into *five* intervals:

- *Interval 1*: represents a period that consists of the average of seven hours for hours 1-7, which are non-working hours of the day;
- *Interval 2*: represents a one hour interval for hour 8, which is a transition hour from non-working hours into working hours of the day;

- *Interval 3*: represents a period that consists of the average of nine hours for hours 9-17, which are working hours of the day;
- *Interval 4*: represent a one hour interval for hour 18, which is a transition hour from working into non-working hours of the day;
- *Interval 5*: represents a period that consists of the average of six hours for hours 19-24, which are non-working hours of the day.

Figure 5-7 shows the power demand of the building, excluding cooling, of the aggregated data for the six monthly groups during the five hour intervals in a day relative to the original data for the days of the months that are grouped together. The electric load for the six monthly groups exhibited similar characteristics: the electric load is the least during non-working hours increased or decreased during transition hours between working and non-working hours and peaked during the working hours of the day. For all the months, the average days showed approximately equal electric loads.

Figure 5-8 shows the cooling load of the aggregated energy use data of the building for the six monthly groups during the five hour intervals in a day relative to the original data for the days of the months that are grouped together. The cooling load for the six groups also exhibited similar characteristics to the electric load profile. However, the cooling load varied throughout the year. *Group 1* had the least cooling load because it consisted of days in heating months. The cooling demand increased from *Group 1* to *Group 6*, where *Group 6* consisted of days in cooling months.

Figure 5-9 shows the heating load of the aggregated energy use of the building for the six groups during the five hour intervals in a day. The heating load in the six groups varied. During the day: the heating load was highest during non working hours, increased or decreased during transition hours between working and non-working hours and was the least during the working hours of the day. During the year, the order of the groups is opposite of the cooling load profile i.e. *Group 1* has the highest heating load and then the heating load decreased from *Group 1* to *Group 6*, where *Group 6* has the least heating load.

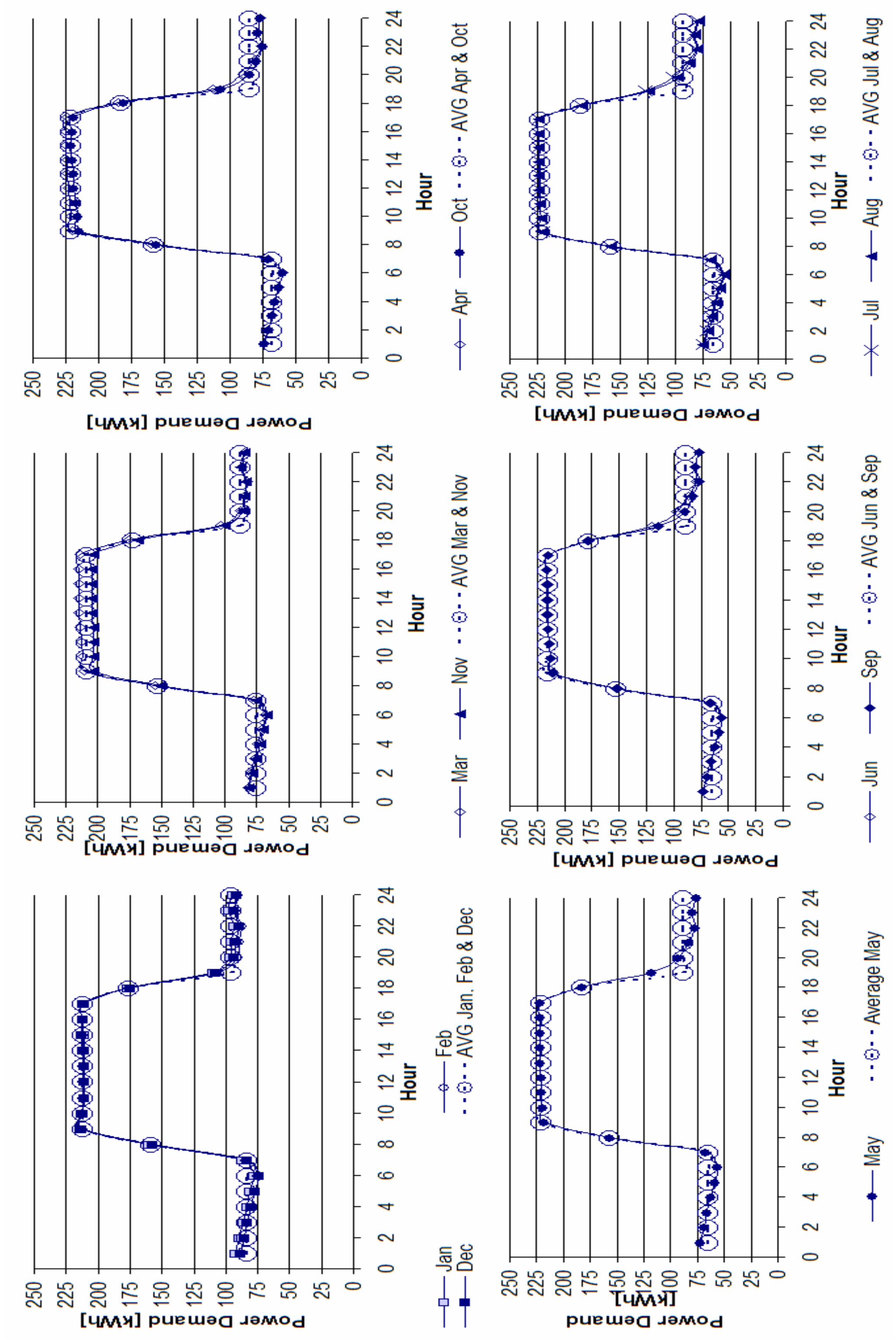



**Figure 5-7: Average hourly power demand in 12 days of the 12 months.**

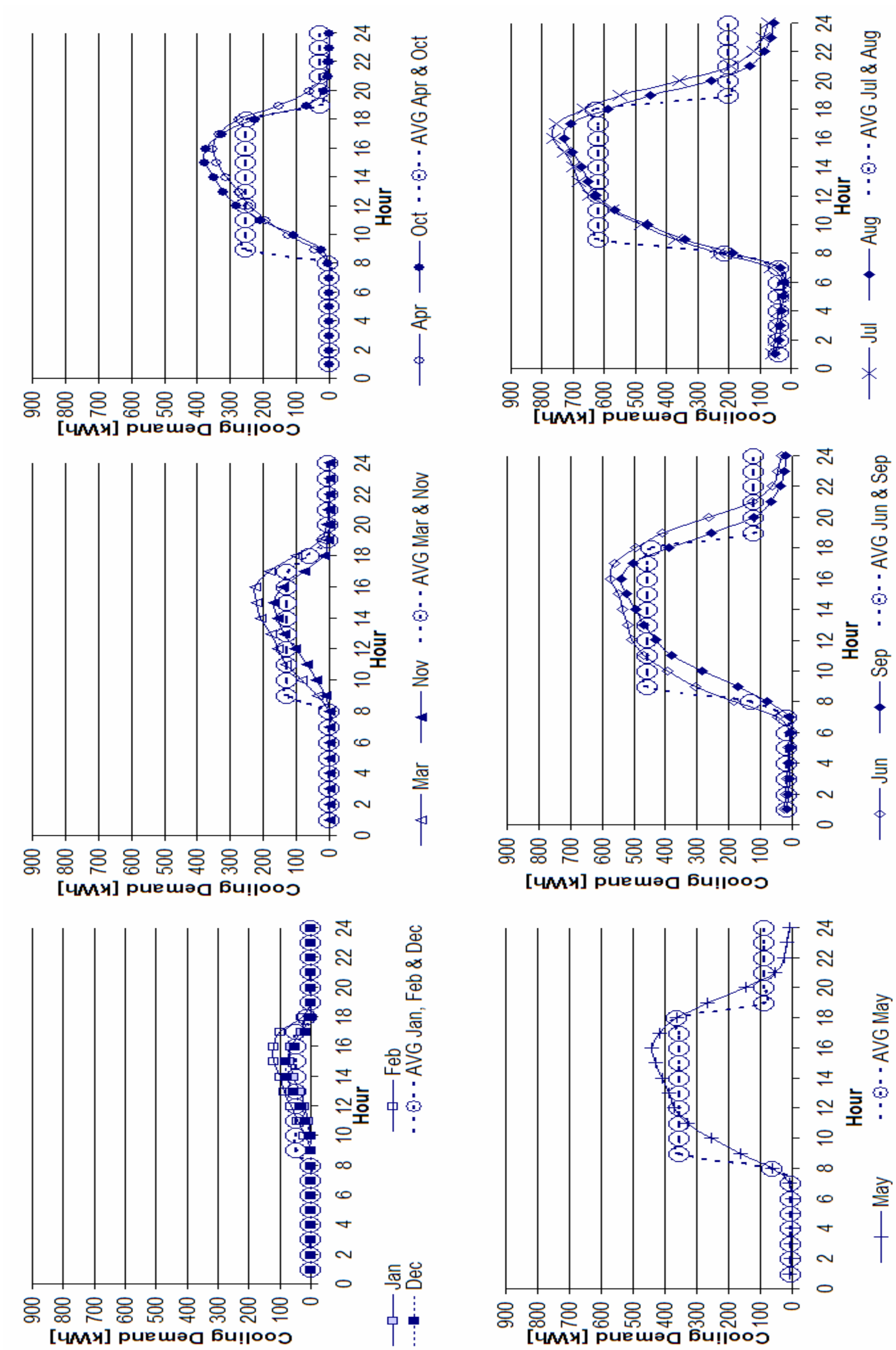



**Figure 5-8: Average hourly cooling demand in 12 days of the 12 months.**

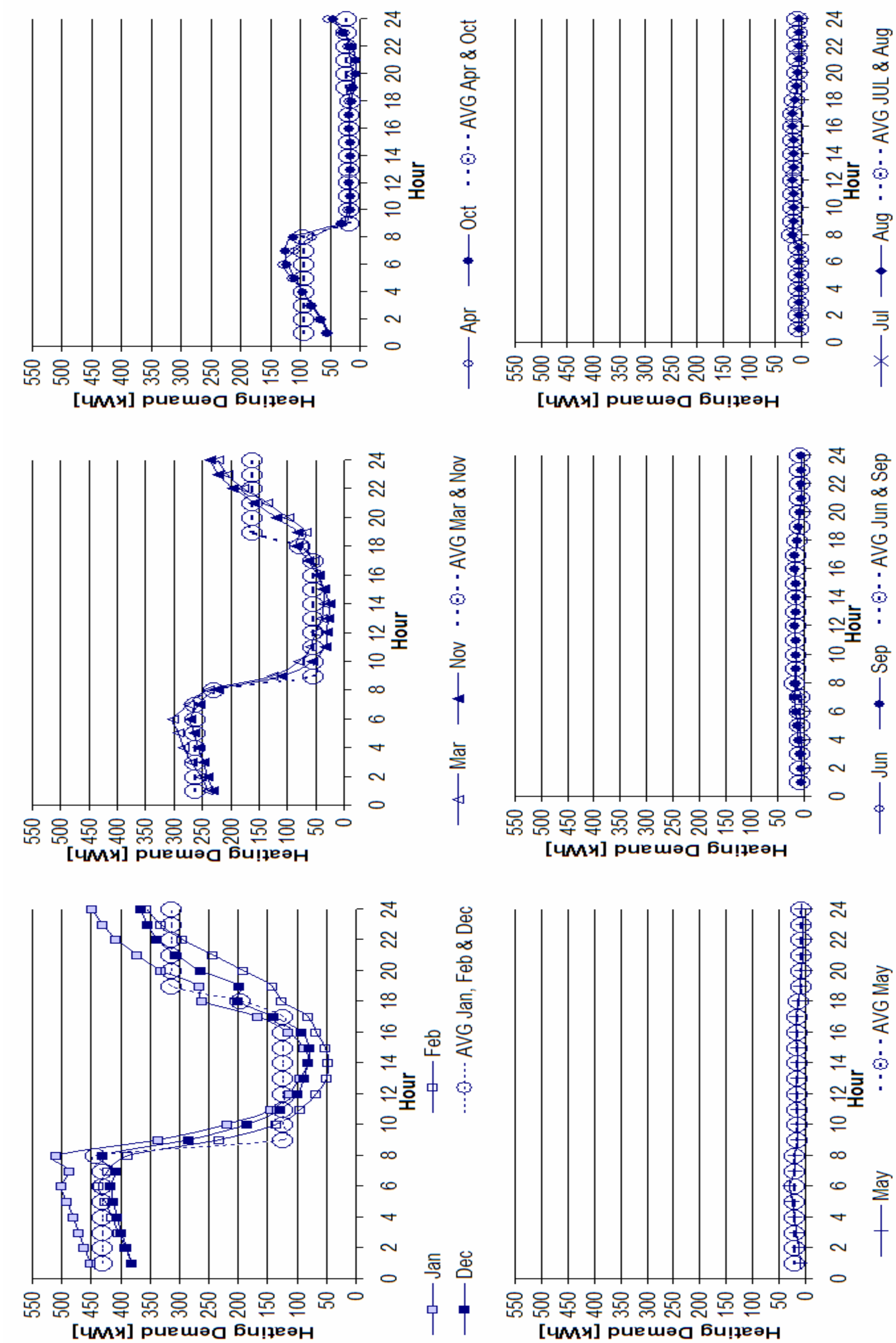



**Figure 5-9: Total hourly heating demand in 12 days of the 12 months.**

## 5.2 LCA OPTIMIZATION MODEL IMPLEMENTATION: INPUTS

The LCA optimization model developed in this research is used to investigate the operation of the hypothetical commercial office building under different objectives. The *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization Model* (described in Chapter 4) are applied to the office building case study and solved for the following objectives:

- Minimizing the life cycle emissions for each of the following indicators: GWP, AP, TOPP, $CO_2$, $SO_2$, and $NO_x$,
- Minimizing the life cycle primary energy consumption, and
- Minimizing the capital and operating costs.

The parameter inputs for the LCA optimization model consist of the cogeneration systems' efficiencies and capacities, potential life cycle emission factors of the energy systems generated from the LCA model, potential life cycle primary energy consumption factors of the energy systems generated from the LCA model, and cost factors associated with the capital and operating costs of the energy systems and evaluated for a study period of ten years. For the complete calculations of the cost factors, refer to Appendix B.

Table 5-4 shows the parameters used to define the cogeneration systems' efficiencies (based on LHV and fuel input) and capacities in the LCA optimization model. The electric conversion efficiency of the US average electric grid is 32% of fuel input (LHV), and is accounted for in the LCA model. The electric conversion efficiency of the NGCC power generation is 49% of fuel input (LHV) and is accounted for in the LCA model.

Table 5-5 shows the life cycle emission factors resulting from unit electrical energy production from all systems except the gas boiler which produced unit heating energy. Table 5-6 shows the life cycle primary energy consumption of the energy systems and Table 5-7 shows the capital and operating cost factors.

The input models (for both the *Hourly LCA Optimization model* and the *Simplified Yearly LCA Optimization model*) in Ampl language is given in Appendix C. The input parameters describing the case building energy use generated from energy simulation for both the *Hourly LCA Optimization model* and the *Simplified Yearly LCA Optimization model* are given in the data inputs files given in Appendix C[11].

**Table 5-4: Cogeneration systems thermodynamic characteristics.**

| **Energy System** | | **Power to Heat Ratio** | **Parameter** | **Max. Capacity [kW]** | **Parameter** | **Min. Capacity [kW]** |
|---|---|---|---|---|---|---|
| **MT** | $PH\ RATIO\ MT_{u100\%}$ | 5.02E-01 | $MaxCap\ MT_{u100\%h}$ | 5.49E+01 | $MinCap\ MT_{u100\%h}$ | 4.80E+01 |
| | $PH\ RATIO\ MT_{u75\%}$ | 4.29E-01 | $MaxCap\ MT_{u75\%h}$ | 3.99E+01 | $MinCap\ MT_{u75\%h}$ | 3.40E+01 |
| | $PH\ RATIO\ MT_{u50\%}$ | 3.53E-01 | $MaxCap\ MT_{u50\%h}$ | 2.48E+01 | $MinCap\ MT_{u50\%h}$ | 2.06E+01 |
| | $PH\ RATIO\ MT_{u25\%}$ | 2.26E-01 | $MaxCap\ MT_{u25\%h}$ | 9.80E+00 | $MinCap\ MT_{u25\%h}$ | 9.00E+00 |
| **ICE** | $PH\ RATIO\ ICE_{u100\%}$ | 6.09E-01 | $MaxCap\ ICE_{u100\%}$ | 1.72E+02 | $MinCap\ ICE_{u100\%}$ | 1.51E+02 |
| | $PH\ RATIO\ ICE_{u75\%}$ | 5.26E-01 | $MaxCap\ ICE_{u75\%}$ | 1.45E+02 | $MinCap\ ICE_{u75\%}$ | 1.13E+02 |
| | $PH\ RATIO\ ICE_{u50\%}$ | 4.38E-01 | $MaxCap\ ICE_{u50\%}$ | 9.70E+01 | $MinCap\ ICE_{u50\%}$ | 7.60E+01 |
| **SOFC** | $PH\ RATIO\ SOFC_{104\%}$ | 1.19E+00 | $MaxCap\ SOFC_{104\%}$ | 1.30E+02 | $MinCap\ SOFC_{104\%}$ | 1.28E+2 |
| | $PH\ RATIO\ SOFC_{100\%}$ | 1.29E+00 | $MaxCap\ SOFC_{100\%}$ | 1.27E+02 | $MinCap\ SOFC_{100\%}$ | 1.21E+02 |
| | $PH\ RATIO\ SOFC_{93\%}$ | 1.50E+00 | $MaxCap\ SOFC_{93\%}$ | 1.20E+02 | $MinCap\ SOFC_{93\%}$ | 1.11E+02 |
| | $PH\ RATIO\ SOFC_{85\%}$ | 1.63E+00 | $MaxCap\ SOFC_{85\%}$ | 1.11E+02 | $MinCap\ SOFC_{85\%}$ | 1.02E+02 |
| | $PH\ RATIO\ SOFC_{78\%}$ | 1.79E+00 | $MaxCap\ SOFC_{78\%}$ | 1.02E+02 | $MinCap\ SOFC_{78\%}$ | 9.15E+01 |
| | $PH\ RATIO\ SOFC_{68\%}$ | 2.08E+00 | $MaxCap\ SOFC_{68\%}$ | 9.14E+01 | $MinCap\ SOFC_{68\%}$ | 8.15E+01 |
| | $PH\ RATIO\ SOFC_{62\%}$ | 2.43E+00 | $MaxCap\ SOFC_{62\%}$ | 8.14E+01 | $MinCap\ SOFC_{62\%}$ | 7.45E+01 |

[11] The models are given for the average electric grid option; however, the same formulations are used when solving the problems with the NGCC power plant option but instead the word "*GRID*" is replaced by "*NGCC*" in both the model and data input files. Also, the emission factors, primary energy usage factors and cost factors for the *GRID* are replaced by those associated with the *NGCC*.

**Table 5-5: Energy systems LC emission factors per unit energy produced.**

| Energy System | | GWP EF [*kg of $CO_2$ Eqv./kWh*] | AP EF [*kg of $SO_2$ Eqv./kWh*] | TOPP EF [*kg of TOPP Eqv./kWh*] | $CO_2$ EF [*kg/kWh*] | $SO_2$ EF [*kg/kWh*] | $NO_x$ EF [*kg/kWh*] |
|---|---|---|---|---|---|---|---|
| MT | *EF* $MT_{u100\%}$ | 7.50E-01 | 1.82E-04 | 3.19E-04 | 7.33E-01 | 1.83E-05 | 2.34E-04 |
| | *EF* $MT_{u75\%}$ | 7.95E-01 | 1.99E-04 | 8.11E-04 | 7.70E-01 | 1.98E-05 | 2.57E-04 |
| | *EF* $MT_{u50\%}$ | 1.07E+00 | 2.60E-04 | 6.39E-03 | 8.96E-01 | 2.38E-05 | 3.38E-04 |
| | *EF* $MT_{u25\%}$ | 1.48E+00 | 4.67E-04 | 3.77E-03 | 1.38E+00 | 3.59E-05 | 6.17E-04 |
| ICE | *EF* $ICE_{u100\%}$ | 6.20E-01 | 2.12E-03 | 4.19E-03 | 5.39E-01 | 1.34E-05 | 3.03E-03 |
| | *EF* $ICE_{u75\%}$ | 6.75E-01 | 2.22E-03 | 4.37E-03 | 5.92E-01 | 1.45E-05 | 3.16E-03 |
| | *EF* $ICE_{u50\%}$ | 7.64E-01 | 2.23E-03 | 4.40E-03 | 6.77E-01 | 1.57E-05 | 3.18E-03 |
| SOFC | *EF* $SOFC_{104\%}$ | 1.05E+00 | 1.23E-04 | 2.08E-04 | 1.04E+00 | 2.22E-05 | 1.44E-04 |
| | *EF* $SOFC_{100\%}$ | 1.02E+00 | 1.21E-04 | 2.04E-04 | 1.01E+00 | 2.20E-05 | 1.41E-04 |
| | *EF* $SOFC_{93\%}$ | 9.61E-01 | 1.51E-04 | 1.94E-04 | 9.49E-01 | 2.15E-05 | 1.34E-04 |
| | *EF* $SOFC_{85\%}$ | 9.41E-01 | 1.13E-04 | 1.91E-04 | 9.30E-01 | 2.13E-05 | 1.31E-04 |
| | *EF* $SOFC_{78\%}$ | 9.23E-01 | 1.12E-04 | 1.88E-04 | 9.11E-01 | 2.12E-05 | 1.29E-04 |
| | *EF* $SOFC_{68\%}$ | 9.23E-01 | 1.12E-04 | 1.88E-04 | 9.11E-01 | 2.12E-05 | 1.29E-04 |
| | *EF* $SOFC_{62\%}$ | 9.05E-01 | 1.10E-04 | 1.85E-04 | 8.94E-01 | 2.10E-05 | 1.27E-04 |
| *EF* Avg. Electric | | 7.87E-01 | 2.61E-03 | 3.46E-03 | 7.36E-01 | 7.77E-04 | 2.55E-03 |
| *EF* NGCC | | 4.45E-01 | 4.14E-04 | 7.69E-04 | 4.31E-01 | 1.04E-05 | 5.80E-04 |
| *EF* Gas Boiler | | 2.40E-01 | 9.89E-05 | 2.09E-04 | 2.35E-01 | 4.83E-06 | 1.35E-04 |

**Table 5-6: Energy systems LC PE consumption factors per unit energy produced.**

| Parameter | Primary Energy Consumption Factor [*kWh/kWh*] |
|---|---|
| *PEC* $MT_{u100\%h}$ | 3.99E+00 |
| *PEC* $MT_{u75\%h}$ | 4.32E+00 |
| *PEC* $MT_{u50\%h}$ | 5.22E+00 |
| *PEC* $MT_{u25\%h}$ | 7.97E+00 |
| *PEC* $ICE_{u100\%}$ | 3.13E+00 |
| *PEC* $ICE_{u75\%}$ | 3.44E+00 |
| *PEC* $ICE_{u50\%}$ | 3.93E+00 |
| *PEC* $SOFC_{104\%}$ | 2.996E+00 |
| *PEC* $SOFC_{100\%}$ | 2.93E+00 |
| *PEC* $SOFC_{93\%}$ | 2.75E+00 |
| *PEC* $SOFC_{85\%}$ | 2.69E+00 |
| *PEC* $SOFC_{78\%}$ | 2.64E+00 |
| *PEC* $SOFC_{68\%}$ | 2.64E+00 |
| *PEC* $SOFC_{62\%}$ | 2.59E+00 |
| *PEC* Avg. Electric | 3.09E+00 |
| *PEC* NGCC | 2.27E+00 |
| *PEC* Gas Boiler | 1.18E+00 |

**Table 5-7: Energy systems LC cost factor per unit energy produced.**

| Parameter | Cost Factor [*$/kWh*] |
|---|---|
| $CF\ MT_{u100\%h}$ | 1.65E-01 |
| $CF\ MT_{u75\%h}$ | 1.74E-01 |
| $CF\ MT_{u50\%h}$ | 1.98E-01 |
| $CF\ MT_{u25\%h}$ | 2.70E-01 |
| $CF\ ICE_{u100\%}$ | 1.19E-01 |
| $CF\ ICE_{u75\%}$ | 1.27E-01 |
| $CF\ ICE_{u50\%}$ | 1.40E-01 |
| $CF\ SOFC_{104\%}$ | 1.43E-01 |
| $CF\ SOFC_{100\%}$ | 1.42E-01 |
| $CF\ SOFC_{93\%}$ | 1.38E-01 |
| $CF\ SOFC_{85\%}$ | 1.37E-01 |
| $CF\ SOFC_{78\%}$ | 1.36E-01 |
| $CF\ SOFC_{68\%}$ | 1.36E-01 |
| $CF\ SOFC_{62\%}$ | 1.35E-01 |
| *CF* Avg. Electric | 7.88E-02 |
| *CF* NGCC | 3.58E-02 |
| *CF* Gas Boiler | 6.80E-02 |

## 5.3 LCA OPTIMIZATION MODEL IMPLEMENTATION: RESULTS & DISCUSSION

The following sections include discussion of the results from the *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization Model* (described in Chapter 4), which are applied to the office building case study. The results include a set of solutions for each of the following problems:

I. Problem set (I) for electric utility *Option (1)*: US average electric grid by implementing the following models:
   (a) *Hourly LCA Optimization Model* and
   (b) *Simplified Yearly LCA Optimization Model*

II. Problem set (II) for electric utility *Option (2)*: NGCC power plant by implementing the following models:
   (a) *Hourly LCA Optimization Model* and
   (b) *Simplified Yearly LCA Optimization Model*

The two sets of problems were then solved for each of the following objective functions:

(a) Minimizing the life cycle emissions for each of the following indicators: GWP, AP, TOPP, $CO_2$, $SO_2$, and $NO_x$,

(b) Minimizing the life cycle primary energy consumption, and

(c) Minimizing the capital and operating costs.

Appendix E representative results for the office building case study obtained from implementing the *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization Model*.

### 5.3.1 Problem Set I: Electric Utility Option (1): USA Average Electric Grid

#### 5.3.1.1 Minimizing LC GWP & $CO_2$

When using the *Hourly LCA Optimization Model* to minimize the GWP and $CO_2$ objective functions in the 12 average days in the months of January through December, the results of the optimization model showed that the ICE cogeneration system was used primarily to meet the power and thermal demand of the building and the MT cogeneration system was used to meet part of the demand, whereas the average electric grid was used minimally to meet part of the electrical demand. Figure 5-10 shows the percent power supply of the energy systems in each day of the months of January through December and Figure 5-11 shows the percent heating supply for the GWP optimization problem. The ICE cogeneration system supplied more than 50% of the electrical and thermal demand with partial use of the MT cogeneration system and minimal use of the average electric grid to meet the electrical demand. Subsequently, the ICE cogeneration system supplied most of the heating demand and the MT cogeneration system supplied part of the heating demand while the gas boiler was only used in heating months to meet part of the heating demand in addition to the cogeneration systems. The absorption chiller was used to meet most of the cooling demand throughout the 12 days and the electric chiller was used partially in the cooling months, as shown in Figure 5-12 for the GWP optimization problem.

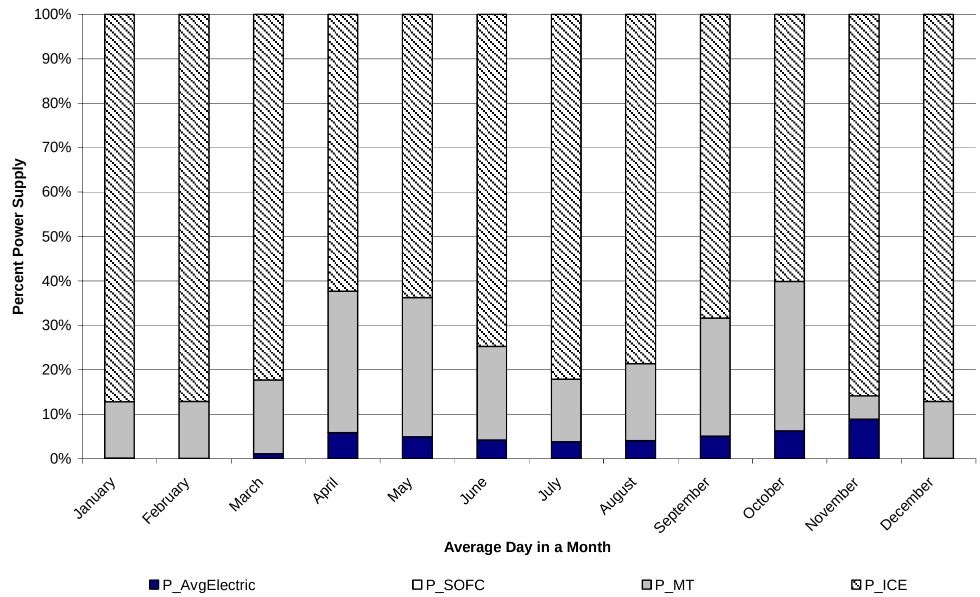



**Figure 5-10: Percent power supply from energy systems: Hourly Model for min GWP.**

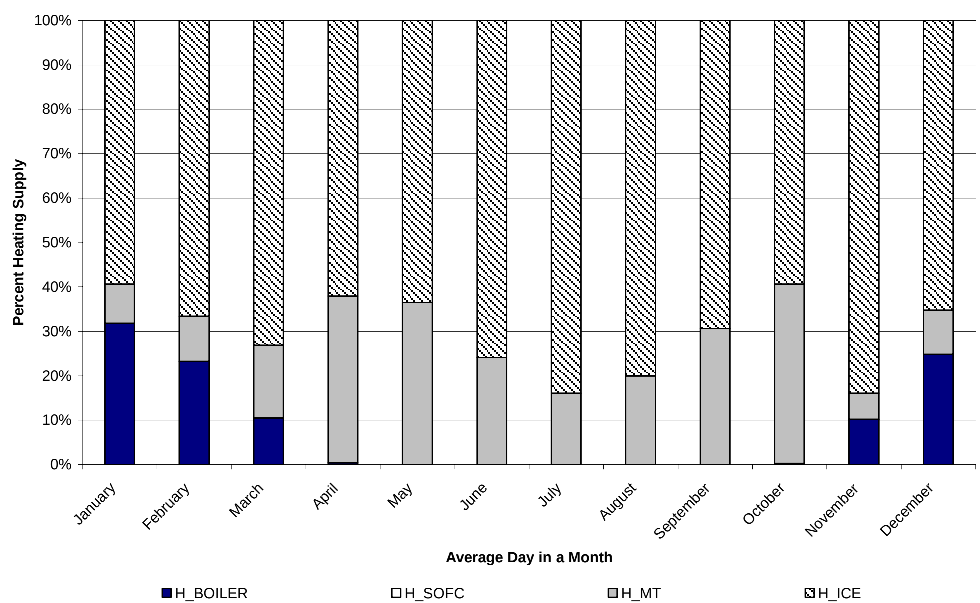



**Figure 5-11: Percent heating supply from energy systems: Hourly LCA Optimization Model for min GWP.**

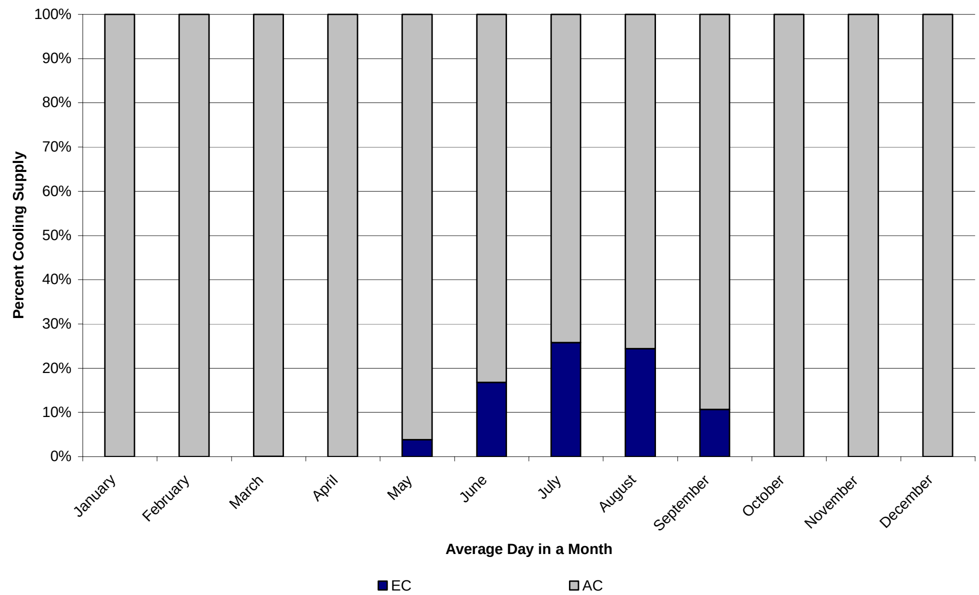



**Figure 5-12: Percent cooling supply from energy systems: Hourly Model for min GWP.**

The analysis of the results indicated that the optimum operational strategy for minimizing GWP and $CO_2$ was electrical load following; the cogeneration systems followed the electric demand required for the miscellaneous equipment electrical energy use and when the cooling demand was higher, mostly during the working hours of the day, the cogeneration systems increased the electrical energy generation above the power demand required for equipment electric use to meet the cooling demand.

The solutions of the optimization problems also indicate the operation of the cogeneration systems at part load levels during the day. For instance, in the average day in October, where the minimum value of the GWP objective function was attained throughout the 12 months (January to December), the optimum operation strategy was to operate the MT and ICE cogeneration units at full load during the working hours of the day (hours 8-18) and the ICE cogeneration system at 75% part load during hour 7 and the MT cogeneration system at 75% part load during hour 19. Whereas, during the non-working hours of the day (hours 1-6 and hour 20-24), the MT cogeneration system operating at full load supplying part of the power requirements, as shown in Figure 5-13. Heat was supplied primarily from the cogeneration system throughout the day: during the working hours heat was supplied partially by the ICE and partially by the MT cogeneration systems, whereas during the non-working hours of the day heat was supplied mainly by the MT cogeneration systems. Cooling was supplied partially by the absorption chiller and partially by the electric chiller during the working hours of the day and mainly by the absorption chiller during the non-working hours of the day.

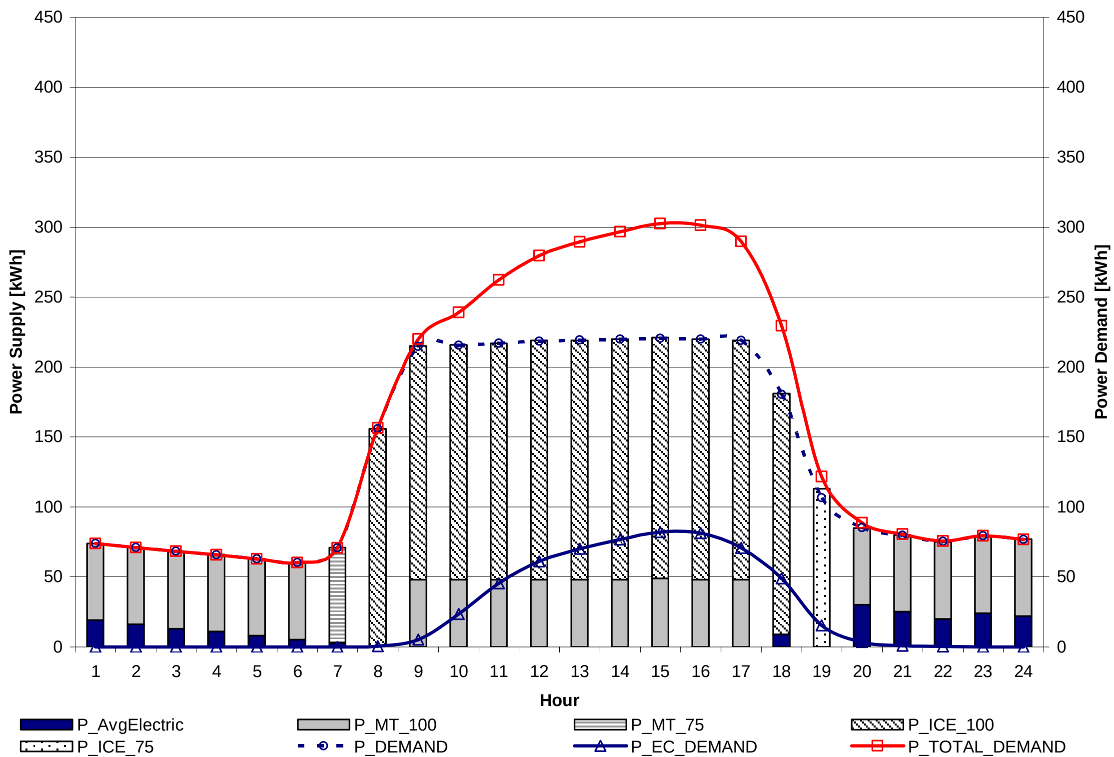



**Figure 5-13: Power demand and supply during a day in October.**

When using the *Simplified LCA Optimization Model* to minimize GWP and $CO_2$ in the year, the results of the optimization model were generally similar to that obtained from the *Hourly LCA Optimization Model* for minimizing GWP and $CO_2$. The results showed the operation of the energy systems in the year versus each day in the 12 months which were evaluated separately in the *Hourly LCA Optimization Model*. Figures 5-14, 5-16 and 5-18 illustrate the results obtained from the *Hourly LCA Optimization Model* used to minimize GWP in the 12 days of the 12 months, which show the operation of the energy systems for power, thermal and cooling energy supply, respectively. Figures 5-15, 5-17 and 5-19 illustrate the results obtained from the *Simplified LCA Optimization Model* used to minimize GWP for the year, which show the operation of energy systems for power, thermal and cooling energy supply, respectively. When comparing the two sets of graphs, the similarities in operational trends are clear.

The solution of the *Simplified LCA Optimization Model* for minimizing GWP in the year showed that the power demand was met primarily by the ICE cogeneration system, while the MT cogeneration system and the average electric grid were used minimally to supplement the power supply. When the cooling demand was relatively higher and the heating demand was lower, as in the months of April through October, the cogeneration systems seemed ideal in meeting the power, thermal and cooling demand of the building with high electric savings especially in the summer months, where the power demand was met before reaching the peak power requirement. This was mainly because the cogenerated heat was used to meet the cooling demand with an absorption chiller, in addition to the partial use of the electric chiller.

In the heating months of January, February and December, the ICE cogeneration system was used primarily to meet the electrical demand of the building and the MT cogeneration system was used partially during the working hours of the day (hours 9-17). Heating was supplied partially by the ICE cogeneration system and partially by the gas boiler during the day except during the working hours of the day when the MT cogeneration system supplied part of the heat in addition to the ICE system. The cooling demand was minimal during those months (less than 50 kWh of cooling demand) and was supplied by the absorption chiller during the working hours of the day.

In the months of March and October, when the heating demand is lower than the heating months but the cooling demand is relatively higher than the heating months, power was supplied mainly by the ICE cogeneration system and partially, during the working hours of the day (hours 9-17), by the average electric grid. Heating was mainly supplied by the ICE except during the early non-working hours of the day (hours 1-7), when the heating demand was higher than the remaining hours of the day, and supplemental heat was supplied by the gas boiler in addition to the ICE system. Cooling was supplied by the absorption chiller during the working hours of the day.

As the cooling demand increased and the heating demand decreased in the months of April and October compared to the heating months of January, February and December as well as the months of March and November, the MT cogenerated system supplied part of the power demand in addition to the grid during the non-working hours of the day (hours 1-7 and hours 19-24) and the MT and ICE cogeneration systems supplied power during the rest of the day. Heating was supplied entirely by the MT and ICE cogeneration systems and cooling was supplied by the absorption chiller driven by heat from the cogeneration systems.

In May the cooling demand increased slightly from April and the heating demand decreased, similar to April and October, the MT cogeneration system supplied part of the power in addition to partial power from the grid supplied power during the non-working hours of the day while the ICE and MT cogeneration systems provided power during the rest of the day. Also, heating was supplied entirely by the MT cogeneration system (during non-working hours of the day) and both the ICE and MT during the working hours of the day. Cooling was supplied mainly by the absorption chiller and only partially by the electric chiller at hour 18 when the heat cogenerated from the cogeneration systems was not sufficient to meet the cooling demand at that hour.

As cooling increased in June as well as September compared to May, power was largely supplied by the ICE cogeneration system and partially by the MT cogeneration system during the working hours of the day. Heating was supplied entirely by the MT and ICE cogeneration systems and cooling was supplied mainly by the absorption chiller except during working hours of the day when the cooling demand was higher than non-working hours of the day and the heat cogenerated from the cogeneration systems was not sufficient to meet the cooling demand and the electric chiller was used to meet part of the cooling demand.

As the cooling demand reached its highest level in July and August, the ICE cogeneration system supplied the entire electrical demand during the day except in the early hours, when the electrical and cooling demand was lower, when it was supplied by the MT cogeneration system and partially by the average electric grid. The heating demand was supplied entirely by the heat cogenerated from the MT and cogeneration systems. The cooling demand was supplied mainly by the absorption chiller except during the working hours of the day when the electric chiller was used to meet part of the cooling demand.

The results of the *Simplified LCA Optimization Model* for minimizing $CO_2$ in the year resemble that obtained for minimizing GWP. For both problems the optimum operational strategy was electrical load following, similar to that obtained from the solution of the *Hourly LCA Optimization Model* for minimizing $CO_2$ and GWP.

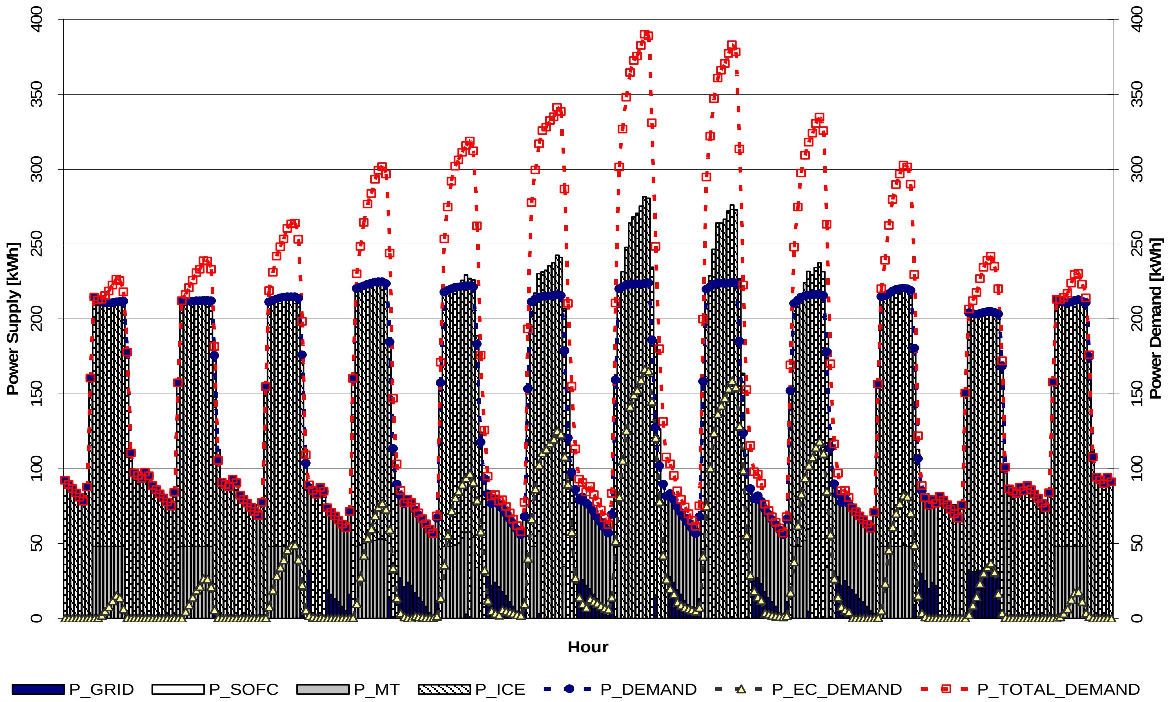



**Figure 5-14: Power supply: solution from the Hourly Model for min GWP.**

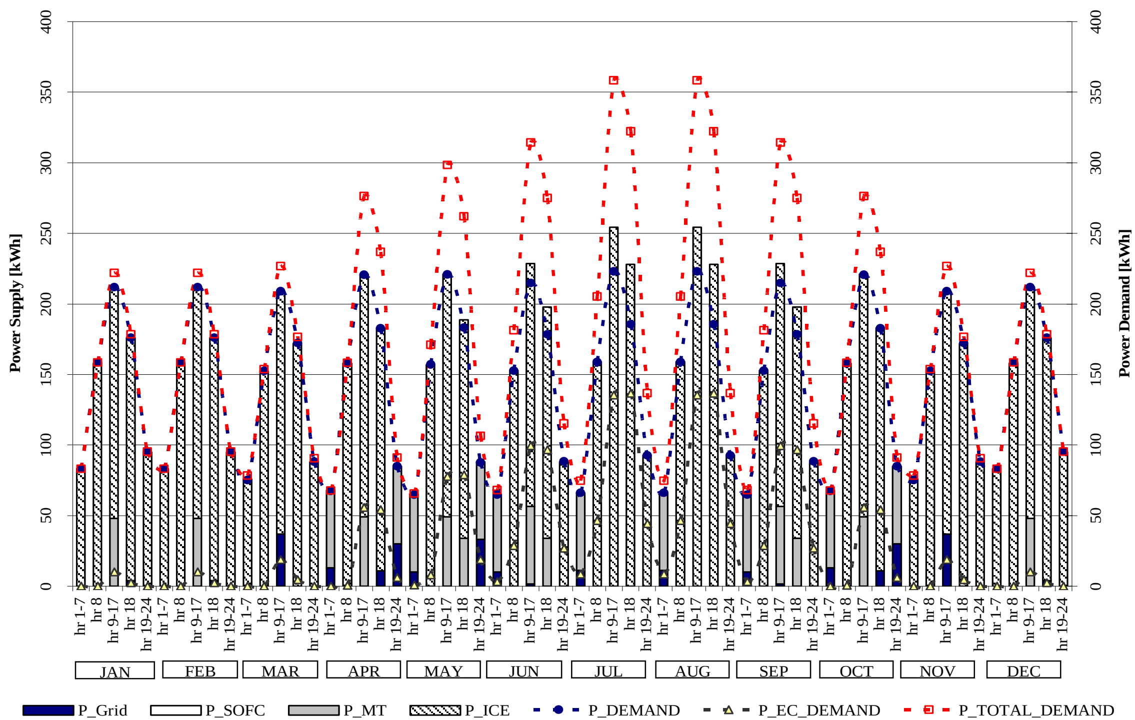



**Figure 5-15: Power supply solution from the Yearly Model for min GWP.**

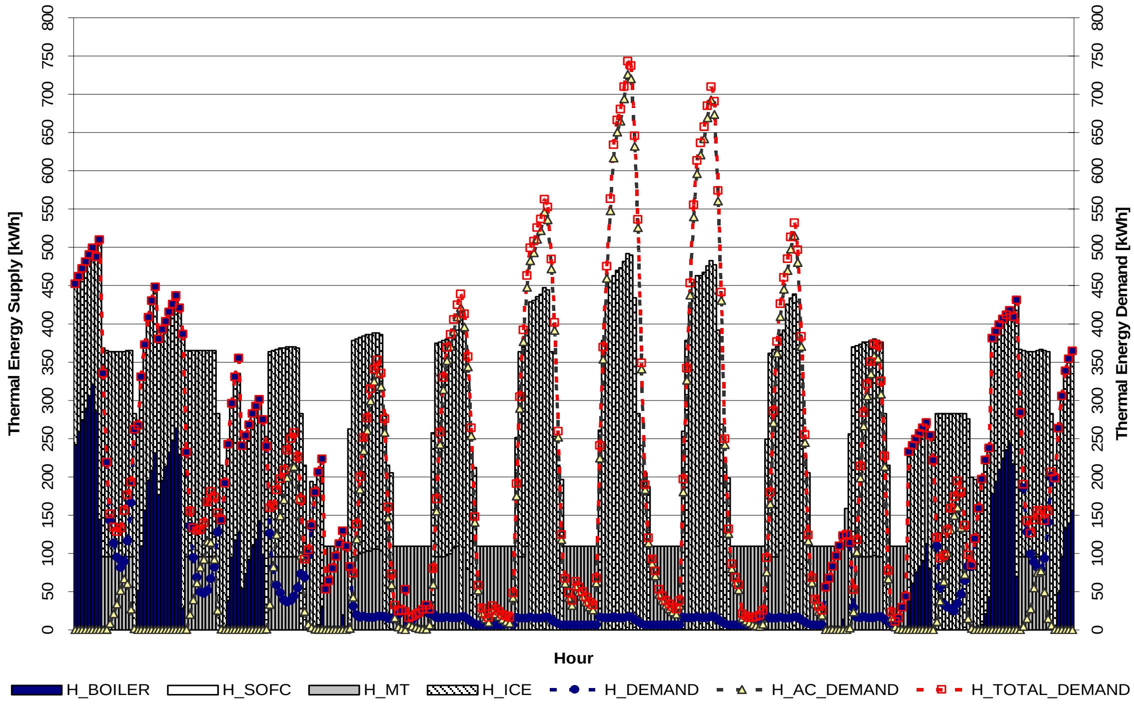



**Figure 5-16: Heating supply solution from the Hourly Model for min GWP.**

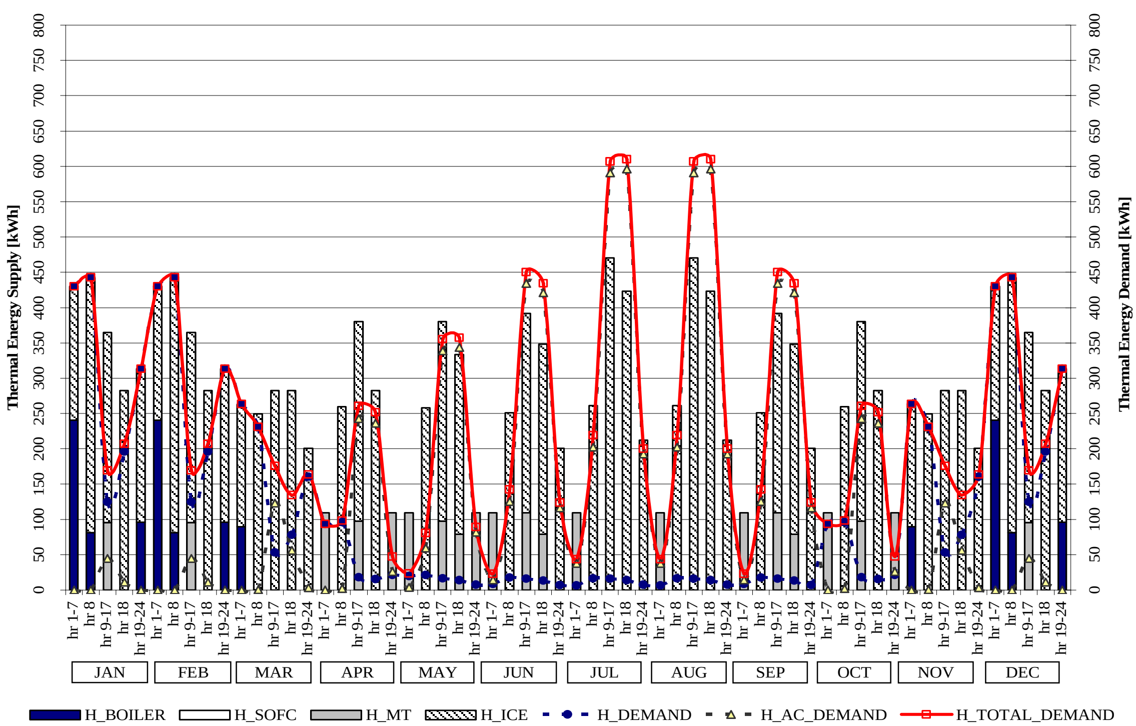



**Figure 5-17: Heating supply solution from the Hourly Model for min GWP.**

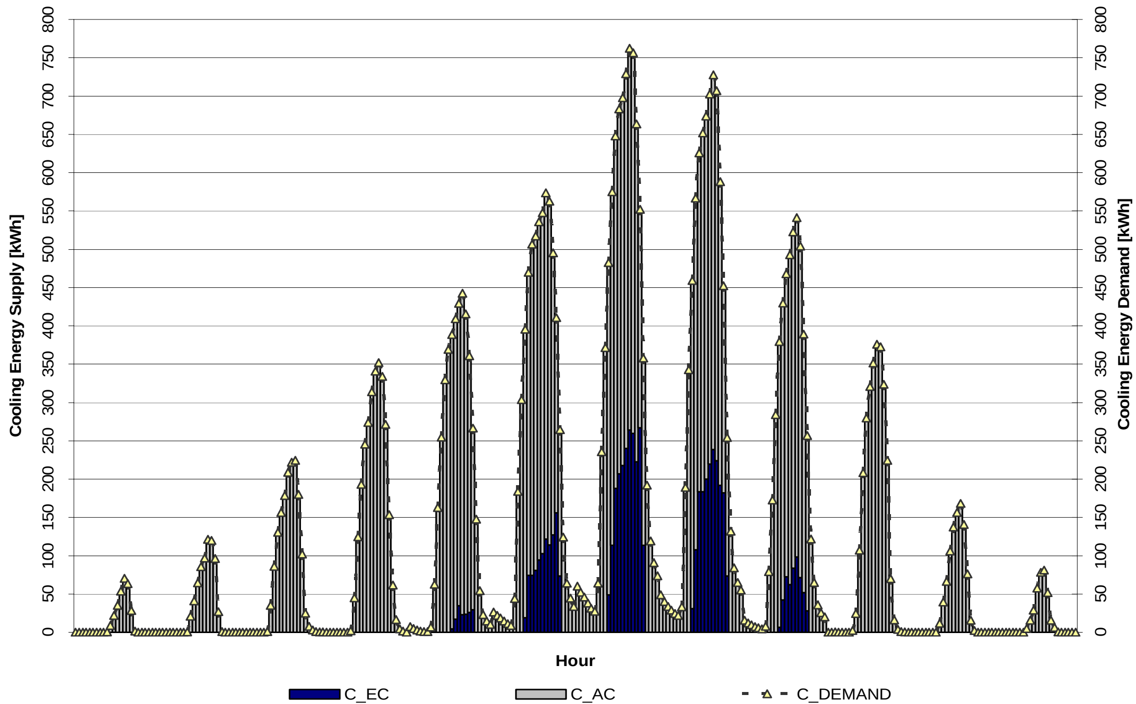



**Figure 5-18: Cooling supply solution from the Hourly Model for min GWP.**

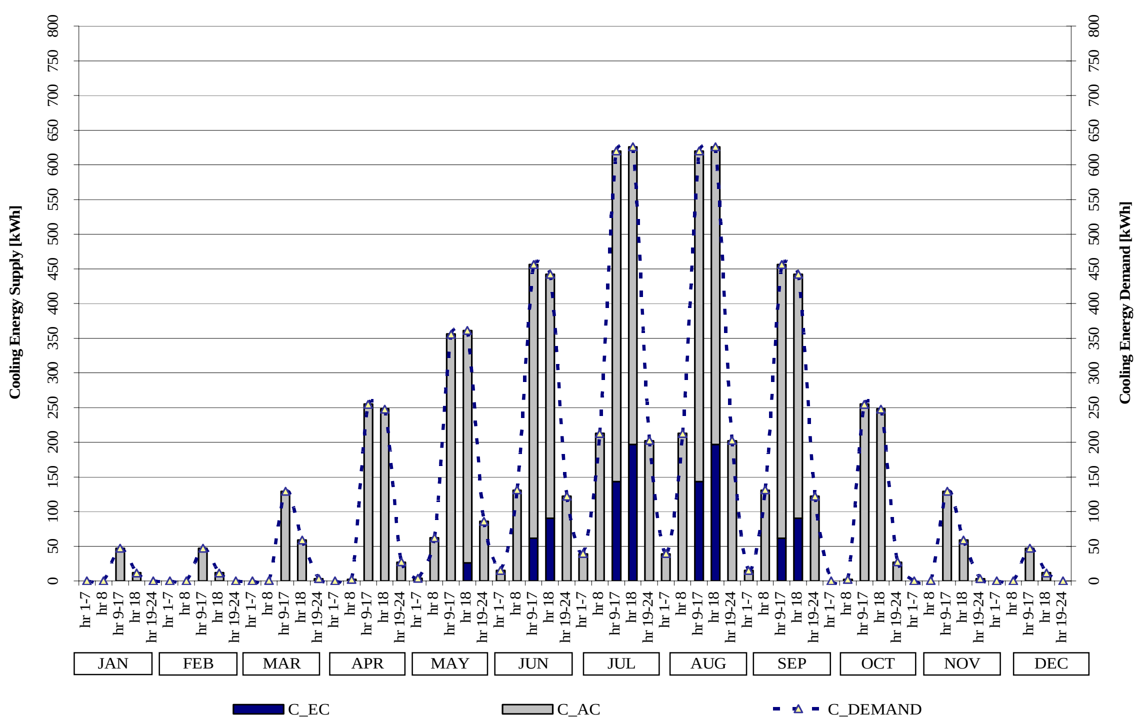



**Figure 5-19: Cooling supply solution from the Model for minGWP.**

From the analysis of the results of the *Hourly LCA Optimization Model*, the GWP and $CO_2$ minimization problems showed similar trends. Figure 5-20 and 5-21 show the normalized objective function values of GWP and $CO_2$, respectively, in the 12 average days of January through December and the calculated values of the indicators corresponding to the minimum objective values. The lowest values of the objective functions in the 12 average days in the year were obtained in the average day in October and the highest values of the objective functions were obtained in the average day in January. The difference in the energy demand of the building in the average days in January and October was due to the relatively higher heating requirement in January (7729 kWh) compared to October (1056 kWh); the electric requirement was approximately equal in the two days, whereas the cooling requirement is higher in October (2684 kWh) as compared to January (284 kWh). Therefore, when minimizing the objective functions (GWP and $CO_2$), the lowest values were obtained on the average day in October mainly because the cogenerated heat from the cogeneration systems was sufficient to meet the heating requirement of the building as well as most of the cooling requirement (using the absorption chiller), whereas in January, supplemental heat from the boiler was required to fulfill the demand.

Generally, the values of the objective functions (GWP and $CO_2$) decreased from January to April and then started to increase from April to July and decreased to the minimum value in October and then increased again in November and December. Table 5-8 and 5-9 show the values of the objective function and the corresponding indicator values. If the highest value of the objective function is considered as 100%, then lowest values of the objective function-less than 10% of the maximum-were attained in the transitional months of April, May, September, and October. The high values of the objective functions (those greater than 60% of the maximum value) were obtained in the heating months of January, February, and December. The objective functions values varied between 10% and 40% of the maximum in the cooling months of June, July, and August as well as the transitional months of March and November.

The results obtained from the *Simplified LCA Optimization Model*, on the other hand, generated the total values of the objective function and the corresponding values of the other indicators. Therefore, unlike the results obtained from the *Hourly LCA Optimization Model*, one cannot determine from the results when the minimum value of the objective function occurs in the year. Figure 5-22 shows the values of GWP in *kg of $CO_2$ equivalents* corresponding to each objective function obtained from the *Simplified LCA Optimization Model* results. When minimizing GWP, $CO_2$ and $SO_2$, the values of GWP obtained were approximately equal, but the values of GWP increased by about 30% when minimizing PE, about 37% when minimizing cost, and up to 50% when minimizing TOPP. Figure 5-23 shows the values of $CO_2$ in kg corresponding to each of the objective functions obtained from the *Simplified LCA Optimization Model*. Similar to the GWP minimization problem, when minimizing $CO_2$, GWP, and $SO_2$, the values of $CO_2$ obtained were approximately equal and increased when minimizing the other objective functions.

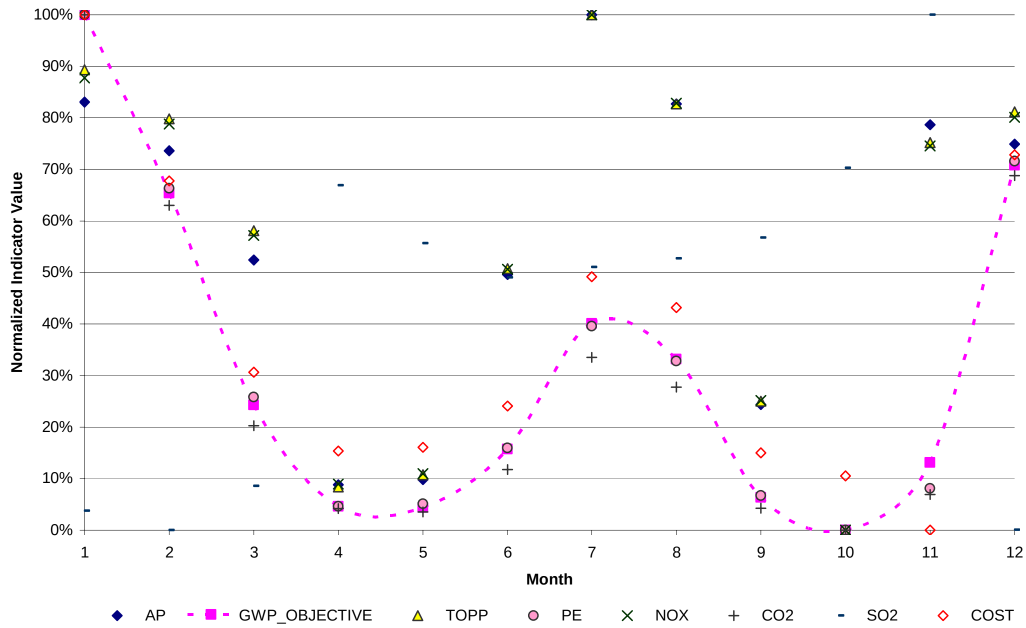



**Figure 5-20: Normalized indicator values corresponding to GWP objective function (Hourly Model).**

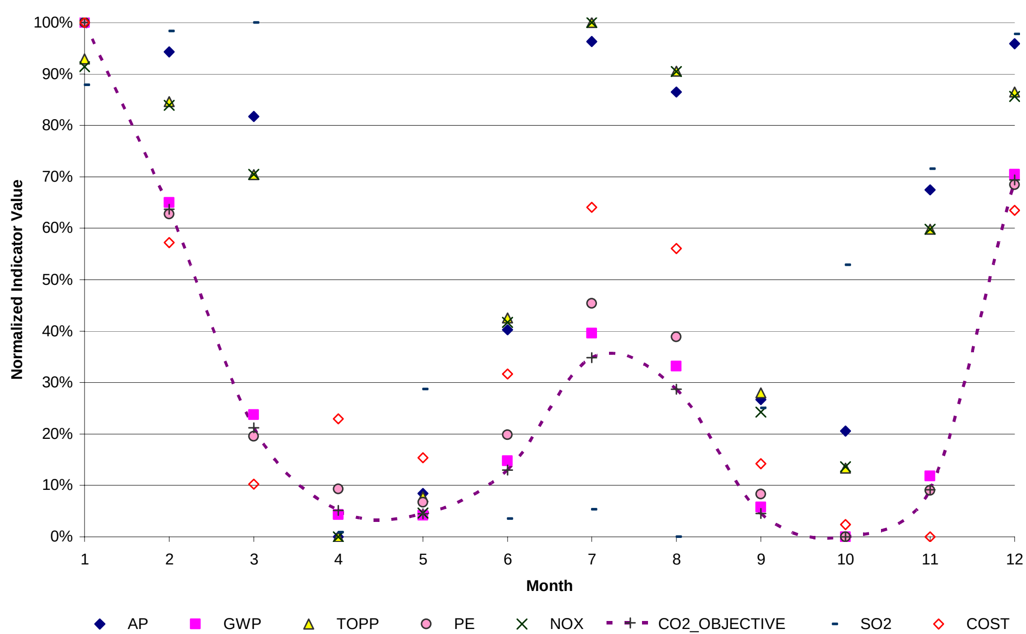


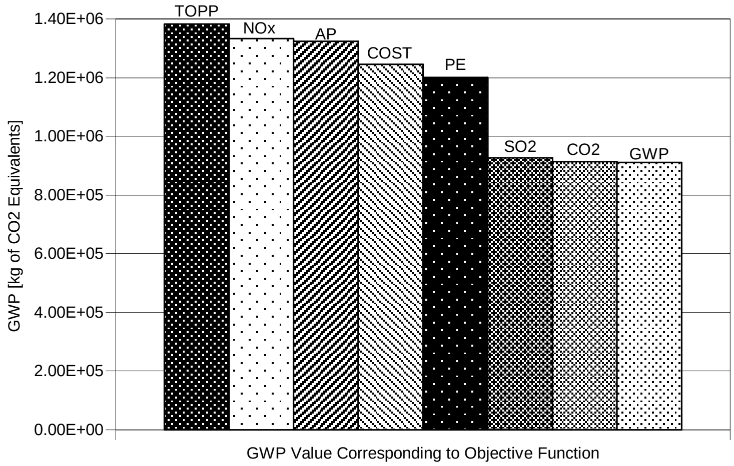

**Figure 5-21: Normalized indicator values corresponding to $CO_2$ objective function (Hourly Model).**

**Table 5-8: GWP objective function values and corresponding indicator values (Hourly Model).**

| | **AP** | **GWP Objective** | **TOPP** | **PE** | **$NO_x$** | **$CO_2$** | **$SO_2$** | **COST** |
|---|---|---|---|---|---|---|---|---|
| January | 6.89E+00 | 3.11E+03 | 1.36E+01 | 1.57E+04 | 9.80E+00 | 2.83E+03 | 7.04E-02 | 5.65E+02 |
| February | 6.67E+00 | 2.80E+03 | 1.32E+01 | 1.42E+04 | 9.49E+00 | 2.54E+03 | 6.28E-02 | 5.18E+02 |
| March | 6.17E+00 | 2.44E+03 | 1.21E+01 | 1.24E+04 | 8.75E+00 | 2.20E+03 | 8.04E-02 | 4.65E+02 |
| April | 5.14E+00 | 2.27E+03 | 9.79E+00 | 1.15E+04 | 7.09E+00 | 2.07E+03 | 2.00E-01 | 4.42E+02 |
| May | 5.17E+00 | 2.27E+03 | 9.90E+00 | 1.15E+04 | 7.15E+00 | 2.07E+03 | 1.77E-01 | 4.43E+02 |
| June | 6.11E+00 | 2.37E+03 | 1.18E+01 | 1.20E+04 | 8.52E+00 | 2.13E+03 | 1.63E-01 | 4.55E+02 |
| July | 7.29E+00 | 2.58E+03 | 1.41E+01 | 1.31E+04 | 1.02E+01 | 2.30E+03 | 1.68E-01 | 4.91E+02 |
| August | 6.89E+00 | 2.52E+03 | 1.33E+01 | 1.28E+04 | 9.63E+00 | 2.26E+03 | 1.71E-01 | 4.83E+02 |
| September | 5.51E+00 | 2.28E+03 | 1.06E+01 | 1.16E+04 | 7.64E+00 | 2.07E+03 | 1.79E-01 | 4.42E+02 |
| October | 4.94E+00 | 2.23E+03 | 9.39E+00 | 1.13E+04 | 6.78E+00 | 2.04E+03 | 2.07E-01 | 4.35E+02 |
| November | 6.79E+00 | 2.34E+03 | 1.30E+01 | 1.17E+04 | 9.35E+00 | 2.09E+03 | 2.68E-01 | 4.20E+02 |
| December | 6.70E+00 | 2.85E+03 | 1.32E+01 | 1.45E+04 | 9.54E+00 | 2.58E+03 | 6.30E-02 | 5.26E+02 |
| Lowest Value | *4.94E+00* | *2.23E+03* | *9.39E+00* | *1.13E+04* | *6.78E+00* | *2.04E+03* | *6.28E-02* | *4.20E+02* |
| Highest Value | *7.29E+00* | *3.11E+03* | *1.41E+01* | *1.57E+04* | *1.02E+01* | *2.83E+03* | *2.68E-01* | *5.65E+02* |

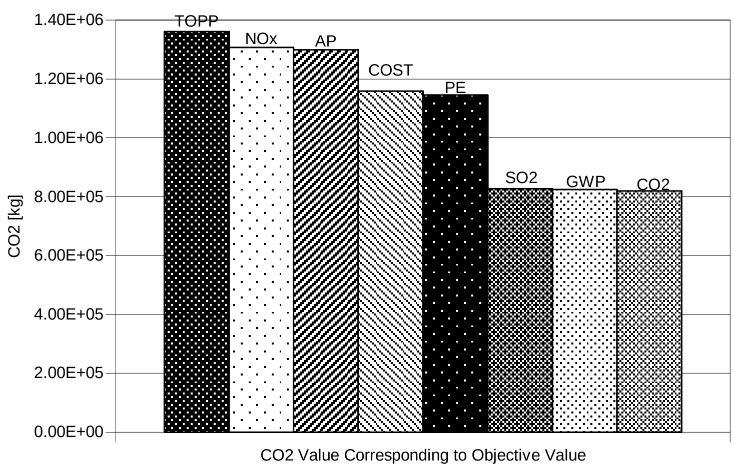
**Table 5-9: CO2 objective function values and corresponding indicator values (Hourly Model).**

| | **AP** | **GWP** | **TOPP** | **$NO_X$** | **PE** | **$CO_2$ Objective** | **$SO_2$** | **COST** |
|---|---|---|---|---|---|---|---|---|
| January | 7.79E+00 | 3.11E+03 | 1.49E+01 | 1.07E+01 | 1.54E+04 | 2.82E+03 | 3.09E-01 | 5.35E+02 |
| February | 7.69E+00 | 2.81E+03 | 1.46E+01 | 1.05E+01 | 1.39E+04 | 2.53E+03 | 3.35E-01 | 4.84E+02 |
| March | 7.45E+00 | 2.45E+03 | 1.41E+01 | 1.02E+01 | 1.21E+04 | 2.18E+03 | 3.40E-01 | 4.28E+02 |
| April | 5.90E+00 | 2.28E+03 | 1.15E+01 | 8.35E+00 | 1.16E+04 | 2.05E+03 | 8.84E-02 | 4.43E+02 |
| May | 6.06E+00 | 2.28E+03 | 1.18E+01 | 8.47E+00 | 1.15E+04 | 2.04E+03 | 1.59E-01 | 4.35E+02 |
| June | 6.66E+00 | 2.37E+03 | 1.31E+01 | 9.43E+00 | 1.21E+04 | 2.11E+03 | 9.51E-02 | 4.54E+02 |
| July | 7.72E+00 | 2.59E+03 | 1.51E+01 | 1.09E+01 | 1.31E+04 | 2.29E+03 | 9.98E-02 | 4.92E+02 |
| August | 7.54E+00 | 2.53E+03 | 1.48E+01 | 1.07E+01 | 1.29E+04 | 2.24E+03 | 8.62E-02 | 4.83E+02 |
| September | 6.41E+00 | 2.29E+03 | 1.25E+01 | 8.98E+00 | 1.16E+04 | 2.04E+03 | 1.50E-01 | 4.33E+02 |
| October | 6.29E+00 | 2.24E+03 | 1.20E+01 | 8.70E+00 | 1.13E+04 | 2.01E+03 | 2.20E-01 | 4.19E+02 |
| November | 7.18E+00 | 2.34E+03 | 1.37E+01 | 9.90E+00 | 1.16E+04 | 2.08E+03 | 2.68E-01 | 4.16E+02 |
| December | 7.72E+00 | 2.85E+03 | 1.46E+01 | 1.06E+01 | 1.41E+04 | 2.57E+03 | 3.34E-01 | 4.91E+02 |
| Lowest Value | *5.90E+00* | *2.24E+03* | *1.15E+01* | *8.35E+00* | *1.13E+04* | *2.01E+03* | *8.62E-02* | *4.16E+02* |
| Highest Value | *7.79E+00* | *3.11E+03* | *1.51E+01* | *1.09E+01* | *1.54E+04* | *2.82E+03* | *3.40E-01* | *5.35E+02* |




| | GWP Value Corresponding to Objective Function |
|---|---|
| TOPP Objective | 1.38E+06 |
| NOx Objective | 1.33E+06 |
| AP Objective | 1.32E+06 |
| COST Objective | 1.25E+06 |
| PE Objective | 1.20E+06 |
| SO2 Objective | 9.27E+05 |
| CO2 Objective | 9.14E+05 |
| GWP Objective | 9.12E+05 |

**Figure 5-22: Normalized indicator values corresponding to GWP objective function (Yearly Model).**




| | CO2 Value Corresponding to Objective Value |
|---|---|
| TOPP Objective | 1.36E+06 |
| NOx Objective | 1.31E+06 |
| AP Objective | 1.30E+06 |
| COST Objective | 1.16E+06 |
| PE Objective | 1.15E+06 |
| SO2 Objective | 8.27E+05 |
| GWP Objective | 8.24E+05 |
| CO2 Objective | 8.19E+05 |

**Figure 5-23: Normalized indicator values corresponding to $CO_2$ objective function (Yearly Model).**

#### 5.3.1.2 Minimizing AP, TOPP & $NO_x$

When using the hourly LCA Optimization Model with the objective functions of minimizing AP, TOPP and $NO_x$ in the 12 average days in the months of January through December, the results of the model were that the SOFC and the MT cogeneration systems were used to meet the energy demand of the building. Figure 5-24 shows the percent power supply of the energy systems in each day in the months of January through December and Figure 5-25 shows the percent heating supply for the AP optimization problems. In the 12 average days, the proportion of the SOFC cogeneration system use to meet the electrical demand of the building increased when the thermal demand was low. Similarly, the proportion of the MT cogeneration system use increased when the thermal demand was high. This trend reflects the characteristics of the cogeneration systems as the SOFC has a higher power to heat ratio compared to the MT cogeneration system whose thermal efficiency ratio is higher than the SOFC. The thermal demand of the building was supplied mainly by the MT cogeneration system and partially by the SOFC and gas boiler when the supplied heat from the SOFC was not sufficient to meet the demand. The cooling demand was supplied mainly by absorption chiller, and in the months of March through October, as the cooling demand increased, the electric chiller supplied part of the cooling demand, as shown in Figure 5-26 for the AP optimization problems.

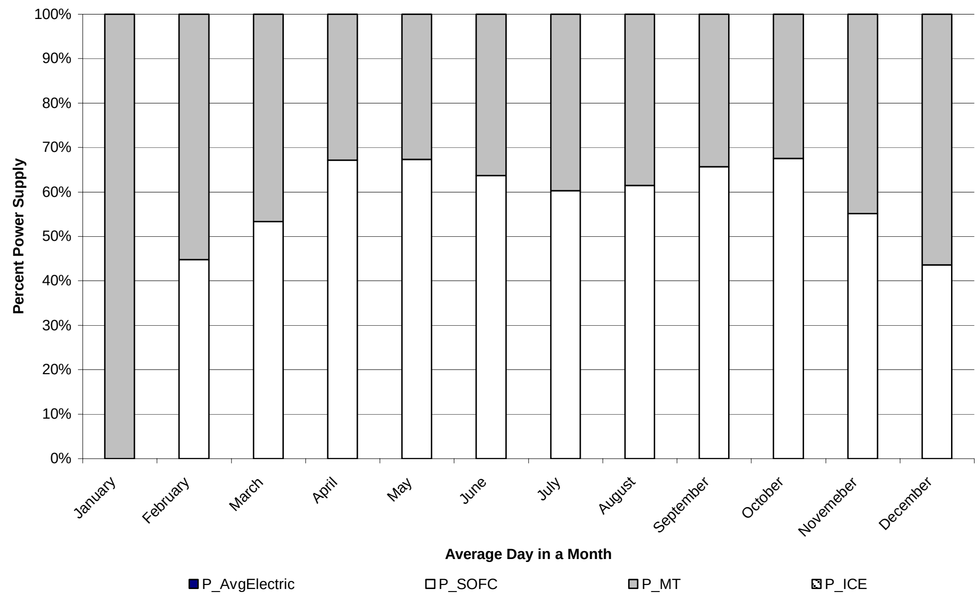



**Figure 5-24: Percent power supply from energy systems: Hourly Model for min AP.**

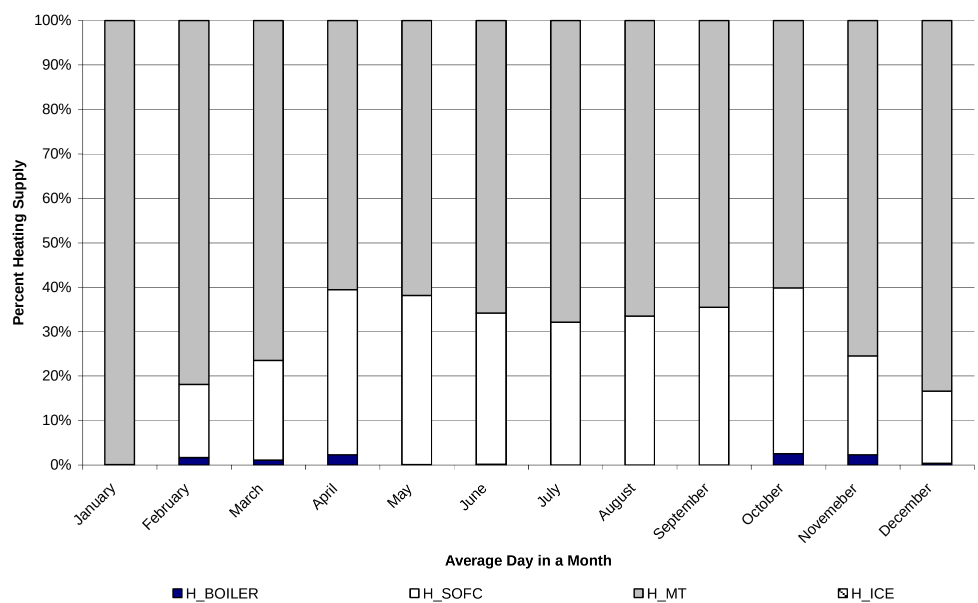



**Figure 5-25: Percent heating supply from energy systems: Hourly Model for min AP.**

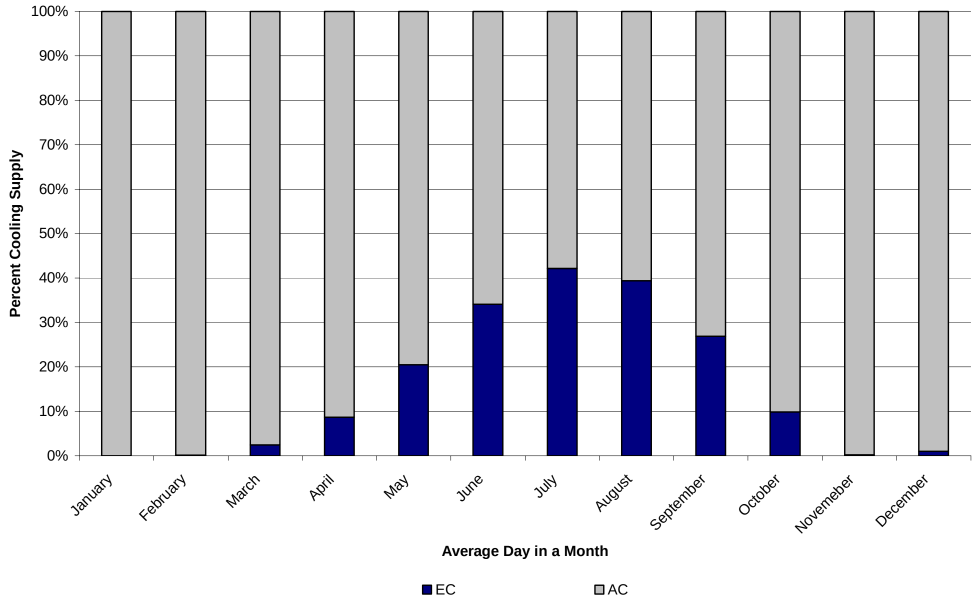



**Figure 5-26: Percent cooling supply from energy systems: Hourly Model for min AP.**

When minimizing AP, the operational strategies varied between the different months. In the heating months of January, February and December, the cogeneration systems followed the electrical load of the building during the working hours of the day (hours 9-18) when the heating demand was low and the electrical demand was high, and followed the thermal load of the building during the non-working hours of the day when the heating demand was high and the electrical load was low (hours 1-7 and hours 19-24). As the cooling demand increased and heating demand decreased considerably, as in the months of April through October, the cogeneration systems followed the electrical load of the building and increased their power production during the working hours of the day with the increase in cooling demand. The use of cogeneration systems in the cooling months proved beneficial because the cogeneration systems were able to meet the energy demand (electrical, thermal and cooling) without reaching the peak energy demand i.e. without producing electrical energy to match the peak electrical demand including cooling with an electric chiller. Instead, the utilization of the thermal energy generated by these systems as well as the electrical energy met the cooling demand by the use of combination of absorption and electric chillers. This proved to be an efficient use of energy.

When using the *Simplified Yearly LCA Optimization Model* to minimize the AP, TOPP and $NO_x$ in the year, the results were generally similar to those obtained from the *Hourly LCA Optimization Model.* Figures 5-27 and 5-28 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization Model* for minimizing AP, respectively. Figures 5-29 and 5-30 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing AP, respectively. Figure 5-31 and 5-32 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing AP, respectively. The graphs indicate the similarity in operational trends of the building.

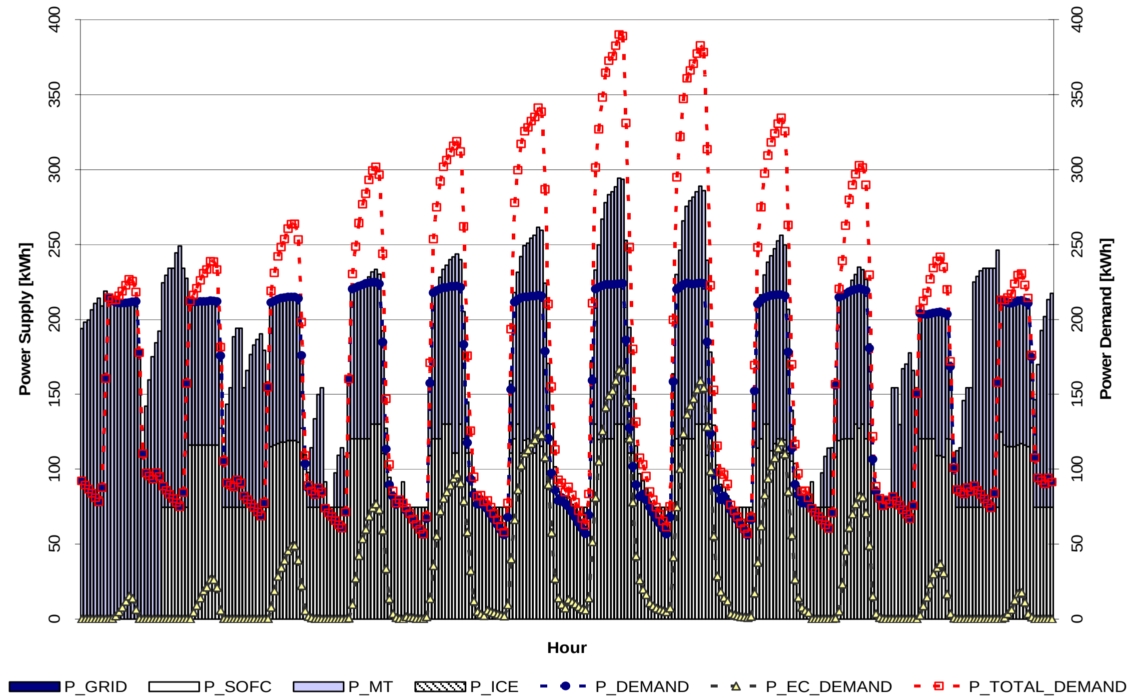



**Figure 5-27: Power supply: solution from Hourly Model for min AP.**

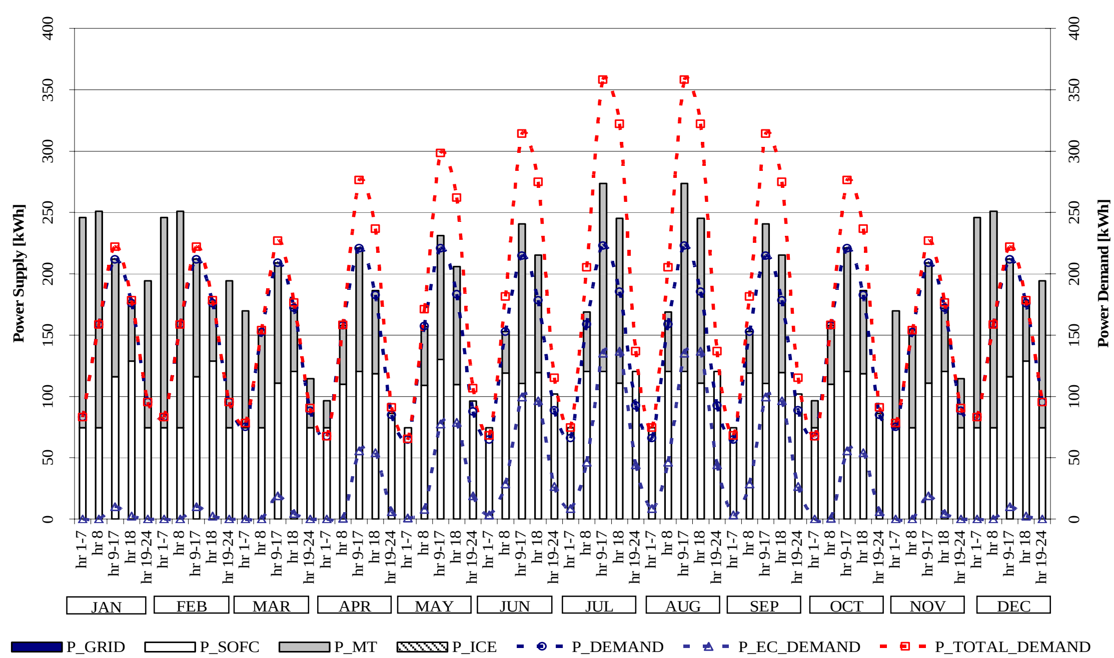



**Figure 5-28: Power supply: solution from Yearly model for min AP**

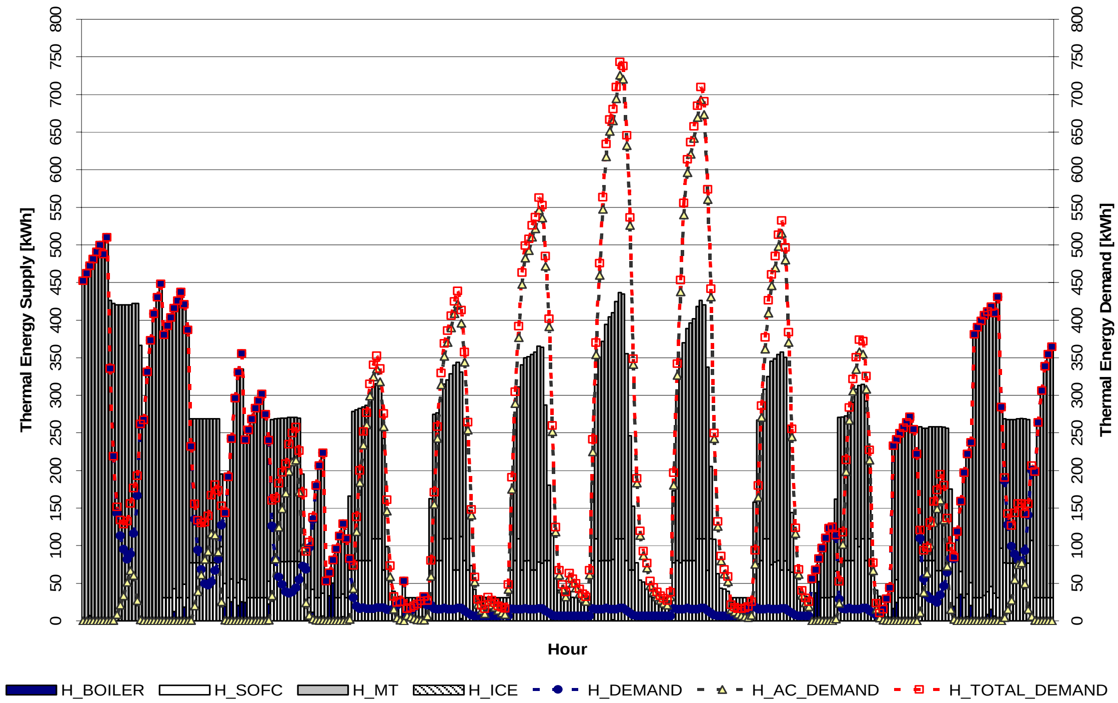



**Figure 5-29: Heating supply: solution from Hourly Model for min AP.**

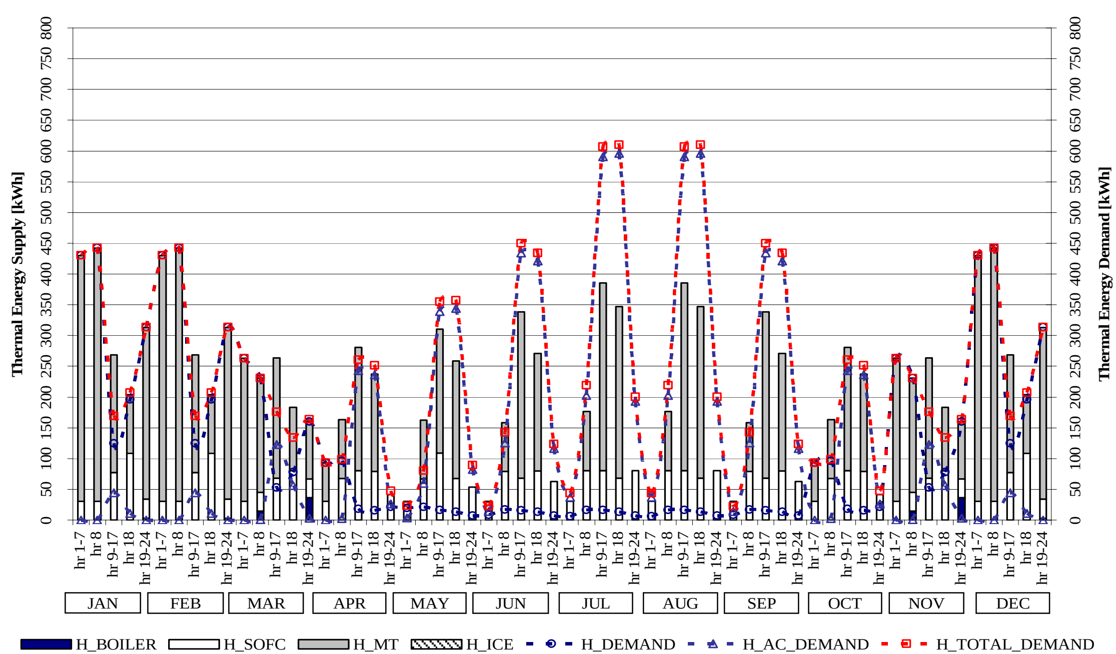



**Figure 5-30: Heating supply: solution from Yearly Model for min AP.**

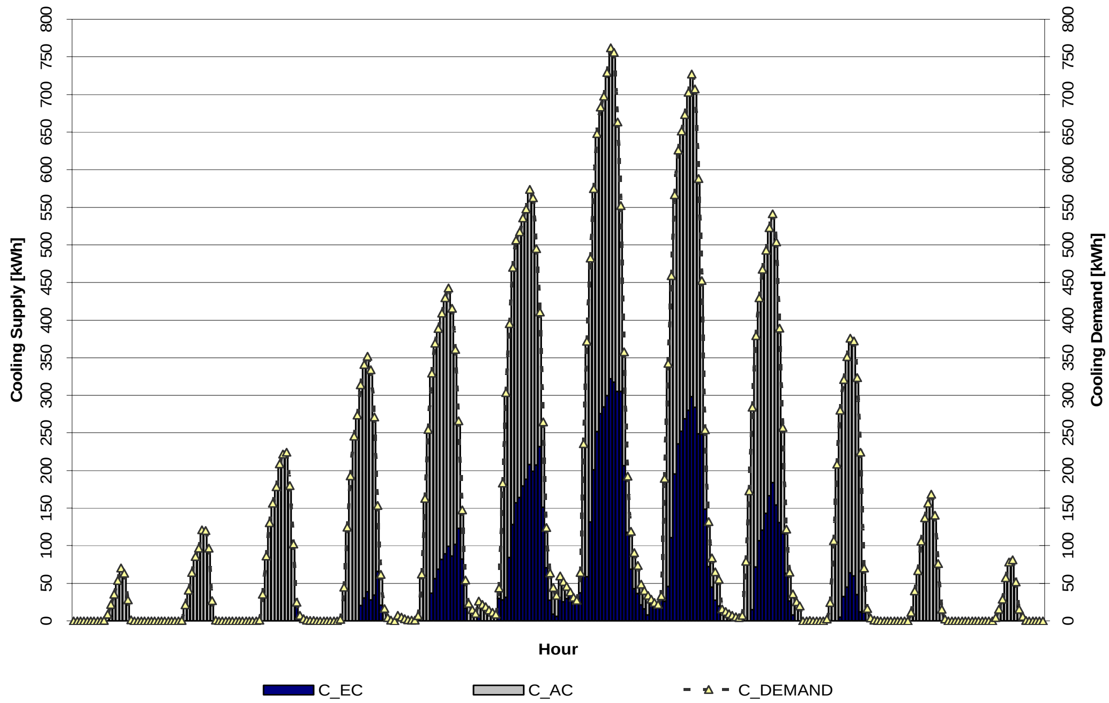



**Figure 5-31: Cooling supply: solution from Hourly LCA for min AP**

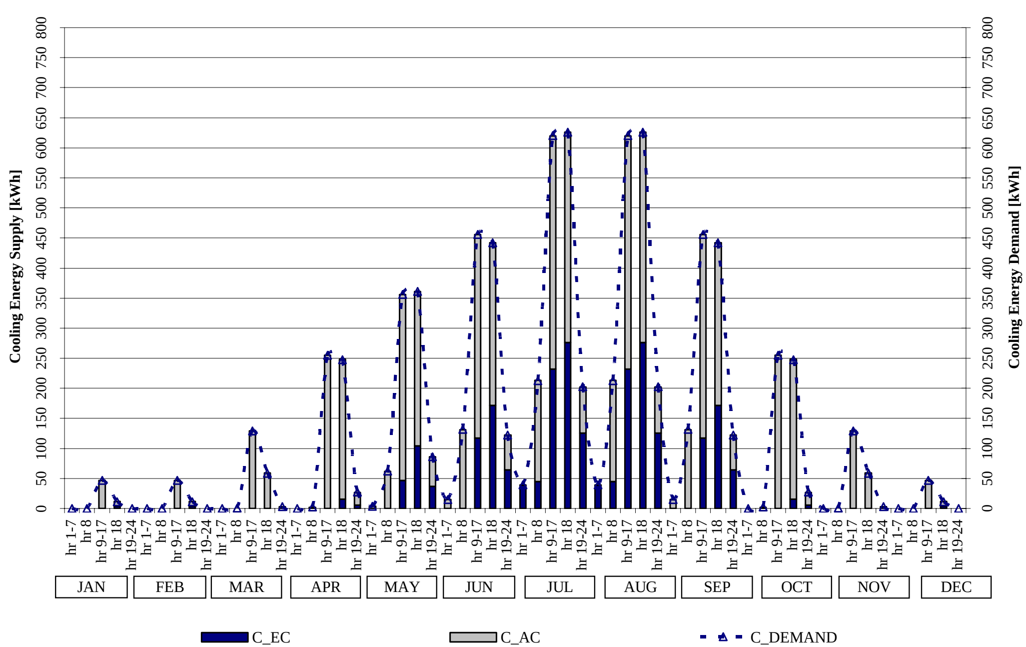



**Figure 5-32: Power supply: solution from Yearly Model for min AP**

When minimizing AP, TOPP and $NO_x$, a similar trend was observed in the solution of the optimization problems. Figures 5-33, 5-34 and 5-35 show the normalized objective function values of AP, TOPP and $NO_x$, respectively, in the 12 average days of January through December and the calculated values of the indicators corresponding to the minimum objective values. Generally, the lowest values of the three objective functions were obtained fir the average day in April, May, September and October, and the highest values were obtained for the average day in January, February, March, November and December. This trend reflects the higher use of the SOFC to meet part of the energy requirement (electrical as well as thermal) when the heating demand is lower as in the month of May versus January. Due to the fact that the SOFC has a higher power to heat ratio than the microturbine, it was suitable to increase its use in May (as well as in the months with lower thermal demand as June through October) as opposed to January (as well as in months with higher thermal demand like February and December). Consequently, because of the lower AP, TOPP and $NO_x$ emission factors of the SOFC as compared to the MT cogeneration system, the partial use of the SOFC cogeneration system to meet part of the electrical and thermal demand of the building (the remaining energy demand was supplied by MT cogeneration system) resulted in lower objective function values in May and the cooling months as compared to January and the heating months.

Tables 5-10, 5-11 and 5-12 show the values of the objective functions, AP, TOPP and $NO_x$ and the corresponding indicator values, respectively. The lowest values of the objective functions (less than 10% of the maximum) were attained in the months of April, May, June, September, and October and then the high values of the objective functions (more than 60% of the maximum) were obtained in the heating months of January, February, and December. The objective functions values varied between 10% and 40% in the cooling months of July, and August as well as the transitional months of March and November.

The results obtained from the *Simplified LCA Optimization Model*, generated the total values of the objective function and the corresponding values of the other indicators. Figures 5-36, 5-37 and 5-38 show the values of AP expressed in *kg of $SO_2$ equivalents*, TOPP expressed in *kg of TOPP equivalents*, and $NO_x$ expressed in *kg* corresponding to each objective function, respectively. When minimizing the AP, TOPP and $NO_x$, the values of AP obtained were approximately equal, but the values of the AP increased almost six times when minimizing PE, about ten times when minimizing GWP and $SO_2$, and about 17 times when minimizing cost. Similarly, the TOPP and $NO_x$ values obtained when minimizing AP, TOPP and $NO_x$ was much lower than the values obtained when minimizing PE, GWP, $CO_2$, $SO_2$ and Cost. These trends reflect the characteristics of the energy systems used when minimizing each of the objective functions. When minimizing GWP, $CO_2$ and $SO_2$, the ICE cogeneration system and to a lesser extent the MT cogeneration system were the main energy systems that were used to meet the energy demand of the building. Since the ICE cogeneration system has higher emission factors for AP, TOPP and $NO_x$ compared to both the SOFC and MT cogeneration systems, the resultant values of AP, TOPP and $NO_x$ when minimizing GWP, $CO_2$ and $SO_2$ were high. When minimizing PE on the other hand, part of the electrical and thermal demand was met by the SOFC cogeneration system in addition to the ICE cogeneration system, the grid and the gas boiler. The partial use of the SOFC cogeneration system when minimizing PE led to a decrease in the values of AP, TOPP and $NO_x$ as compared to the values obtained when minimizing GWP, $CO_2$ and $SO_2$. The values of AP, TOPP and $NO_x$ were considerably high when minimizing cost because the electric demand was met by using the average electric grid and to a lesser extent the ICE cogeneration system, which have high AP, TOPP and $NO_x$ emission factors compared to the SOFC and MT cogeneration systems.

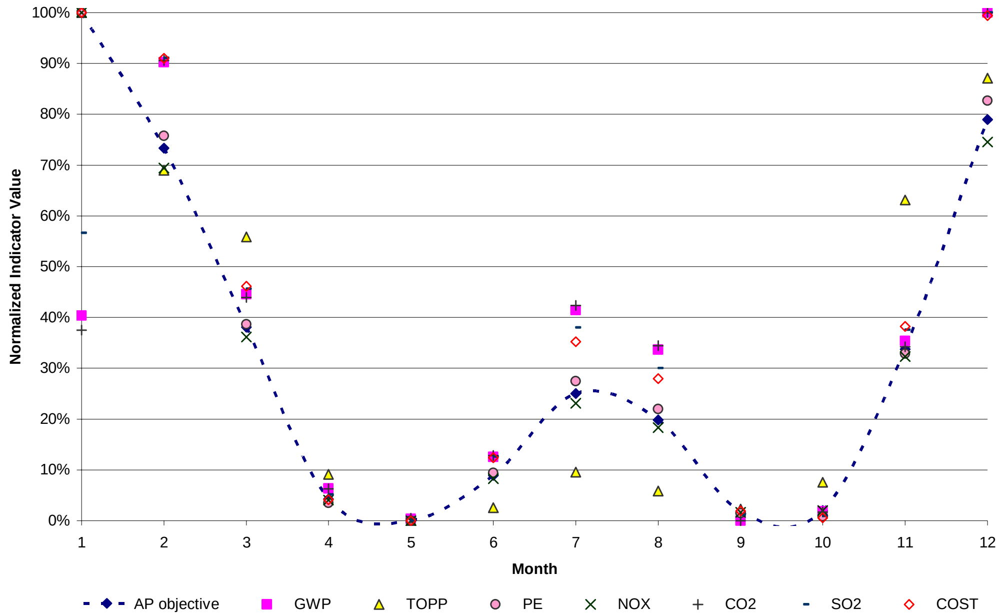



**Figure 5-33: Normalized indicator values corresponding to AP objective function (Hourly Model).**

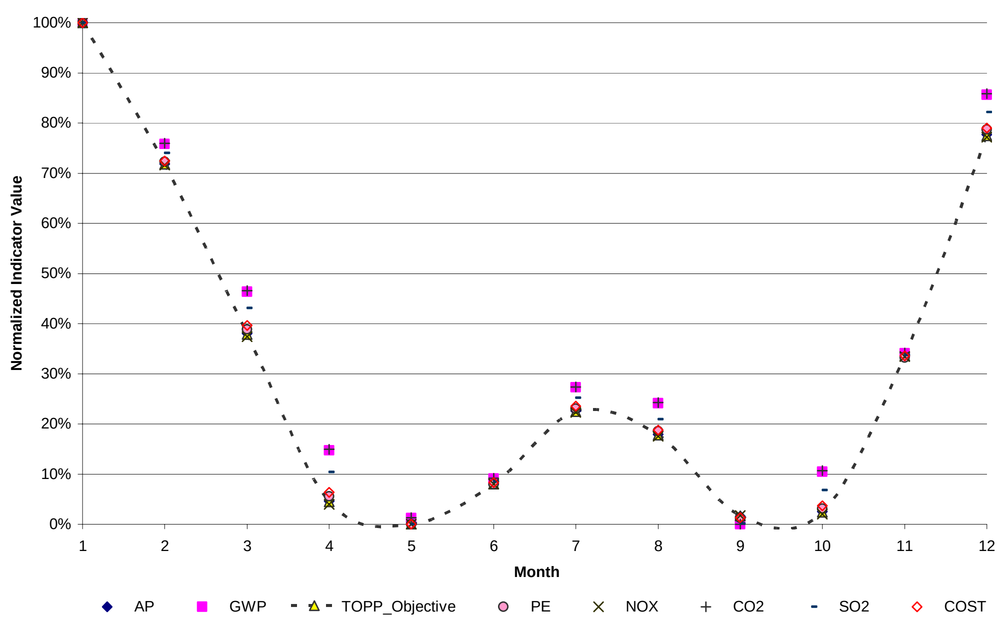



**Figure 5-34: Normalized indicator values corresponding to TOPP objective function (Hourly Model).**

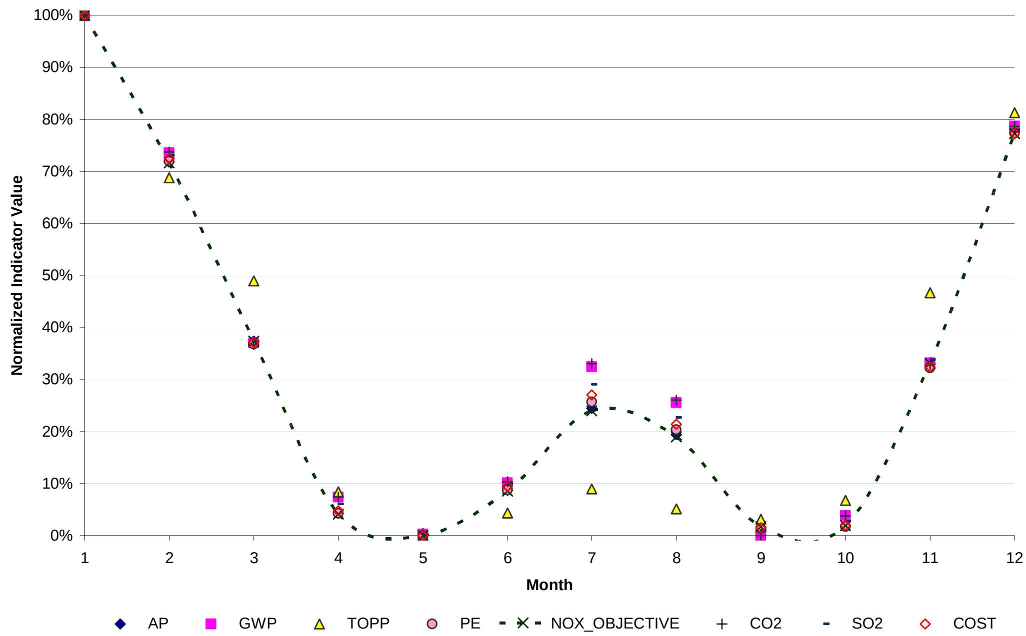



**Figure 5-35: Normalized indicator values corresponding to $NO_x$ objective function (Hourly Model).**

**Table 5-10: Indicator value functions corresponding to AP objective function (Hourly Model).**

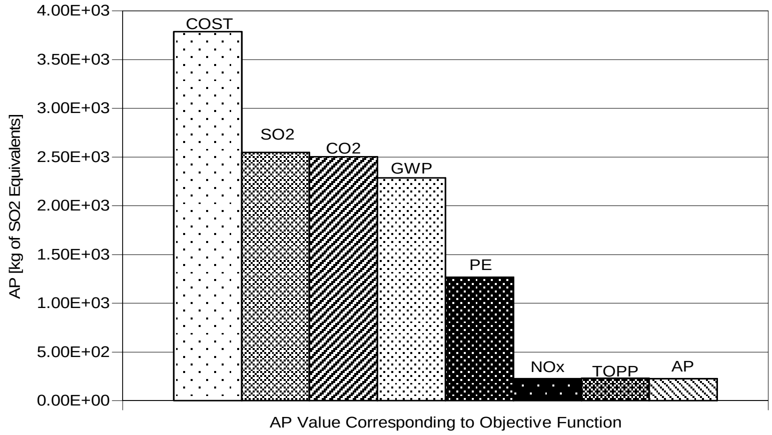
| | AP Objective | GWP | TOPP | PE | $NO_x$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 9.01E-01 | 3.65E+03 | 2.81E+00 | 1.96E+04 | 1.16E+00 | 3.55E+03 | 9.01E-02 | 8.00E+02 |
| February | 7.91E-01 | 4.24E+03 | 2.21E+00 | 1.76E+04 | 9.88E-01 | 4.15E+03 | 1.01E-01 | 7.75E+02 |
| March | 6.46E-01 | 3.70E+03 | 1.97E+00 | 1.45E+04 | 7.99E-01 | 3.62E+03 | 8.68E-02 | 6.51E+02 |
| April | 5.06E-01 | 3.24E+03 | 1.08E+00 | 1.15E+04 | 6.17E-01 | 3.19E+03 | 7.45E-02 | 5.35E+02 |
| May | 4.89E-01 | 3.17E+03 | 9.01E-01 | 1.12E+04 | 5.94E-01 | 3.12E+03 | 7.29E-02 | 5.23E+02 |
| June | 5.25E-01 | 3.32E+03 | 9.50E-01 | 1.20E+04 | 6.41E-01 | 3.26E+03 | 7.68E-02 | 5.58E+02 |
| July | 5.92E-01 | 3.66E+03 | 1.08E+00 | 1.35E+04 | 7.25E-01 | 3.60E+03 | 8.45E-02 | 6.21E+02 |
| August | 5.70E-01 | 3.57E+03 | 1.01E+00 | 1.31E+04 | 6.98E-01 | 3.51E+03 | 8.21E-02 | 6.01E+02 |
| September | 4.95E-01 | 3.17E+03 | 9.45E-01 | 1.14E+04 | 6.04E-01 | 3.12E+03 | 7.33E-02 | 5.29E+02 |
| October | 4.97E-01 | 3.19E+03 | 1.05E+00 | 1.13E+04 | 6.06E-01 | 3.14E+03 | 7.32E-02 | 5.25E+02 |
| November | 6.28E-01 | 3.59E+03 | 2.10E+00 | 1.40E+04 | 7.77E-01 | 3.51E+03 | 8.44E-02 | 6.29E+02 |
| December | 8.14E-01 | 4.36E+03 | 2.56E+00 | 1.82E+04 | 1.02E+00 | 4.26E+03 | 1.03E-01 | 7.98E+02 |
| Lowest Value | 4.89E-01 | 3.17E+03 | 9.01E-01 | 1.12E+04 | 5.94E-01 | 3.12E+03 | 7.29E-02 | 5.23E+02 |
| Highest Value | 9.01E-01 | 4.36E+03 | 2.81E+00 | 1.96E+04 | 1.16E+00 | 4.26E+03 | 1.03E-01 | 8.00E+02 |

**Table 5-11: Indicator value functions corresponding to TOPP objective function (Hourly Model).**

| | AP | GWP | TOPP Objective | PE | $NO_x$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 9.45E-01 | 5.00E+03 | 1.64E+00 | 2.12E+04 | 1.18E+00 | 4.91E+03 | 1.18E-01 | 9.38E+02 |
| February | 8.17E-01 | 4.55E+03 | 1.42E+00 | 1.85E+04 | 1.02E+00 | 4.47E+03 | 1.06E-01 | 8.23E+02 |
| March | 6.62E-01 | 3.99E+03 | 1.14E+00 | 1.51E+04 | 8.15E-01 | 3.93E+03 | 9.23E-02 | 6.87E+02 |
| April | 5.10E-01 | 3.40E+03 | 8.75E-01 | 1.18E+04 | 6.18E-01 | 3.35E+03 | 7.73E-02 | 5.49E+02 |
| May | 4.89E-01 | 3.15E+03 | 8.40E-01 | 1.12E+04 | 5.95E-01 | 3.10E+03 | 7.25E-02 | 5.23E+02 |
| June | 5.25E-01 | 3.30E+03 | 9.04E-01 | 1.20E+04 | 6.42E-01 | 3.24E+03 | 7.64E-02 | 5.57E+02 |
| July | 5.92E-01 | 3.64E+03 | 1.02E+00 | 1.35E+04 | 7.26E-01 | 3.58E+03 | 8.41E-02 | 6.21E+02 |
| August | 5.70E-01 | 3.58E+03 | 9.82E-01 | 1.31E+04 | 6.98E-01 | 3.52E+03 | 8.21E-02 | 6.01E+02 |
| September | 4.96E-01 | 3.12E+03 | 8.53E-01 | 1.14E+04 | 6.05E-01 | 3.08E+03 | 7.26E-02 | 5.28E+02 |
| October | 5.00E-01 | 3.32E+03 | 8.59E-01 | 1.16E+04 | 6.07E-01 | 3.27E+03 | 7.56E-02 | 5.38E+02 |
| November | 6.42E-01 | 3.76E+03 | 1.11E+00 | 1.46E+04 | 7.92E-01 | 3.70E+03 | 8.80E-02 | 6.62E+02 |
| December | 8.43E-01 | 4.73E+03 | 1.46E+00 | 1.91E+04 | 1.05E+00 | 4.65E+03 | 1.10E-01 | 8.51E+02 |
| Lowest Value | 4.89E-01 | 3.12E+03 | 8.40E-01 | 1.12E+04 | 5.95E-01 | 3.08E+03 | 7.25E-02 | 5.23E+02 |
| Highest Value | 9.45E-01 | 5.00E+03 | 1.64E+00 | 2.12E+04 | 1.18E+00 | 4.91E+03 | 1.18E-01 | 9.38E+02 |

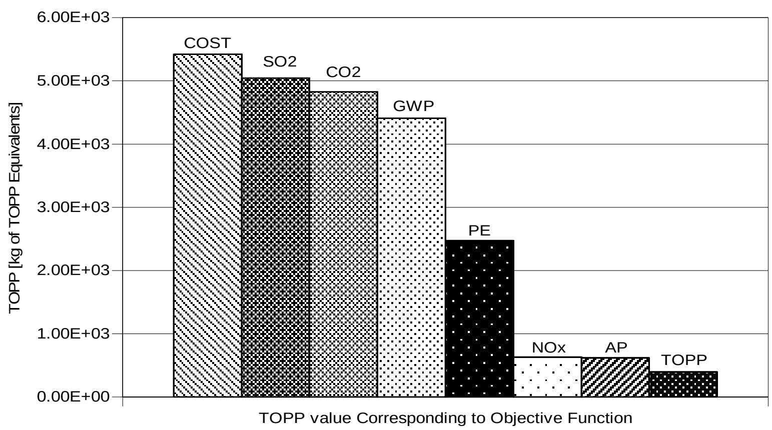
**Table 5-12: Indicator value functions corresponding to $NO_x$ objective function (Hourly Model).**

| | AP | GWP | TOPP | PE | $NO_x$ Objective | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 9.10E-01 | 4.72E+03 | 2.79E+00 | 2.03E+04 | 1.14E+00 | 4.61E+03 | 1.13E-01 | 8.84E+02 |
| February | 7.91E-01 | 4.31E+03 | 2.21E+00 | 1.77E+04 | 9.86E-01 | 4.22E+03 | 1.02E-01 | 7.84E+02 |
| March | 6.46E-01 | 3.75E+03 | 1.84E+00 | 1.46E+04 | 7.98E-01 | 3.67E+03 | 8.80E-02 | 6.57E+02 |
| April | 5.07E-01 | 3.29E+03 | 1.09E+00 | 1.16E+04 | 6.16E-01 | 3.24E+03 | 7.56E-02 | 5.41E+02 |
| May | 4.89E-01 | 3.18E+03 | 9.34E-01 | 1.13E+04 | 5.94E-01 | 3.14E+03 | 7.31E-02 | 5.24E+02 |
| June | 5.25E-01 | 3.34E+03 | 1.01E+00 | 1.20E+04 | 6.41E-01 | 3.28E+03 | 7.71E-02 | 5.58E+02 |
| July | 5.92E-01 | 3.68E+03 | 1.10E+00 | 1.36E+04 | 7.25E-01 | 3.62E+03 | 8.47E-02 | 6.21E+02 |
| August | 5.70E-01 | 3.57E+03 | 1.03E+00 | 1.31E+04 | 6.98E-01 | 3.52E+03 | 8.22E-02 | 6.01E+02 |
| September | 4.96E-01 | 3.18E+03 | 9.92E-01 | 1.14E+04 | 6.03E-01 | 3.13E+03 | 7.35E-02 | 5.29E+02 |
| October | 4.97E-01 | 3.24E+03 | 1.06E+00 | 1.14E+04 | 6.04E-01 | 3.19E+03 | 7.42E-02 | 5.30E+02 |
| November | 6.29E-01 | 3.69E+03 | 1.80E+00 | 1.42E+04 | 7.75E-01 | 3.62E+03 | 8.66E-02 | 6.40E+02 |
| December | 8.15E-01 | 4.39E+03 | 2.44E+00 | 1.82E+04 | 1.02E+00 | 4.30E+03 | 1.04E-01 | 8.02E+02 |
| Lowest Value | 4.89E-01 | 3.18E+03 | 9.34E-01 | 1.13E+04 | 5.94E-01 | 3.13E+03 | 7.31E-02 | 5.24E+02 |
| Highest Value | 9.10E-01 | 4.72E+03 | 2.79E+00 | 2.03E+04 | 1.14E+00 | 4.61E+03 | 1.13E-01 | 8.84E+02 |



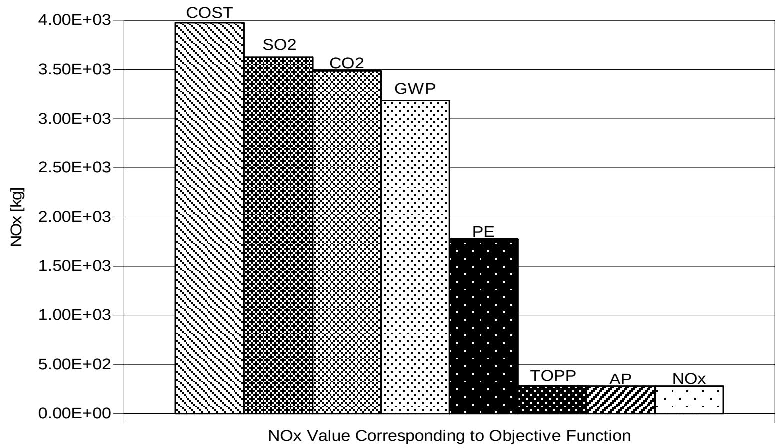

| | *AP Value Corresponding to Objective Function* |
|---|---|
| *COST Objective* | *3.79E+03* |
| *SO2 Objective* | *2.55E+03* |
| *CO2_objective* | *2.50E+03* |
| *GWP Objective* | *2.28E+03* |
| *PE Objective* | *1.27E+03* |
| *NOx Objective* | *2.25E+02* |
| *TOPP Objective* | *2.29E+02* |
| *AP Objective* | *2.25E+02* |

**Figure 5-36: Normalized indicator values corresponding to AP objective function (Yearly Model).**




| | *TOPP value Corresponding to Objective Function* |
|---|---|
| *COST Objective* | *5.42E+03* |
| *SO2 Objective* | *5.05E+03* |
| *CO2 Objective* | *4.83E+03* |
| *GWP Objective* | *4.41E+03* |
| *PE Objective* | *2.47E+03* |
| *NOx Objective* | *6.29E+02* |
| *AP Objective* | *6.20E+02* |
| *TOPP Objective* | *3.95E+02* |

**Figure 5-37: Normalized indicator values corresponding to TOPP objective function (Yearly Model).**




| | *NOx Value Corresponding to Objective Function* |
|---|---|
| *COST Objective* | *3.98E+03* |
| *SO2 Objective* | *3.63E+03* |
| *CO2 Objective* | *3.49E+03* |
| *GWP Objective* | *3.19E+03* |
| *PE Objective* | *1.77E+03* |
| *TOPP Objective* | *2.82E+02* |
| *AP Objective* | *2.78E+02* |
| *NOx Objective* | *2.78E+02* |

**Figure 5-38: Normalized indicator values corresponding to $NO_x$ objective function (Yearly Model).**

#### 5.3.1.3 Minimizing $SO_2$

When using the *hourly LCA Optimization Model* to minimize the $SO_2$ objective function in the 12 average days in the months of January through December, the results of the optimization model showed that the ICE cogeneration system was used primarily to meet the power and thermal demand of the building. Figures 5-39 and 5-40 show the percent power supply and percent heating supply of the energy systems in each day of the months of January through December, respectively. The ICE cogeneration system supplied more than 80% of the electrical demand with partial use of the MT cogeneration system. Subsequently, the ICE cogeneration system supplied most of the heating demand and the MT cogeneration system supplied part of the heating demand while the gas boiler was only used in heating months to meet part of the heating demand in addition to the cogeneration systems. The absorption chiller was used to meet most of the cooling demand throughout the 12 days and the electric chiller was used partially in the cooling months, as shown in Figure 5-41.

Although $SO_2$ is a major constituent of AP-which is expressed in $SO_2$ equivalents (1 kg of $SO_2$ equals 1.0 kg of $SO_2$ equivalents), when minimizing AP, the SOFC and MT cogeneration systems were used to meet the energy requirements of the building. These systems were compared to the ICE cogeneration system because their $NO_x$ emission factors were considerably lower than the ICE cogeneration system. $NO_x$ (which is another major constituent of AP (1 kg of $NO_x$ equals 0.696 kg in $SO_2$ equivalents)) resulted in an offset of $SO_2$ contribution to AP.

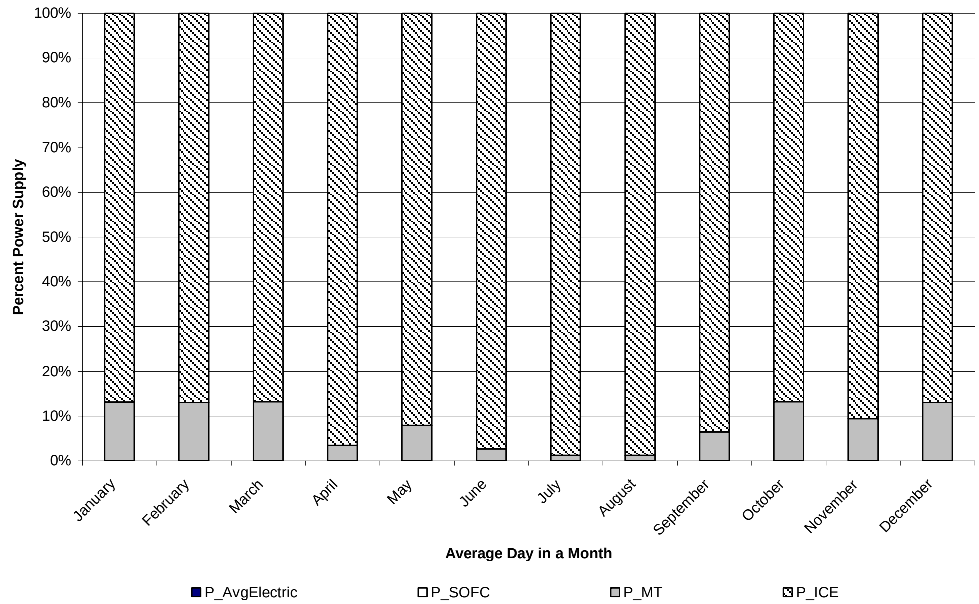



**Figure 5-39: Percent power supply from energy systems: Hourly Model for min $SO_2$.**

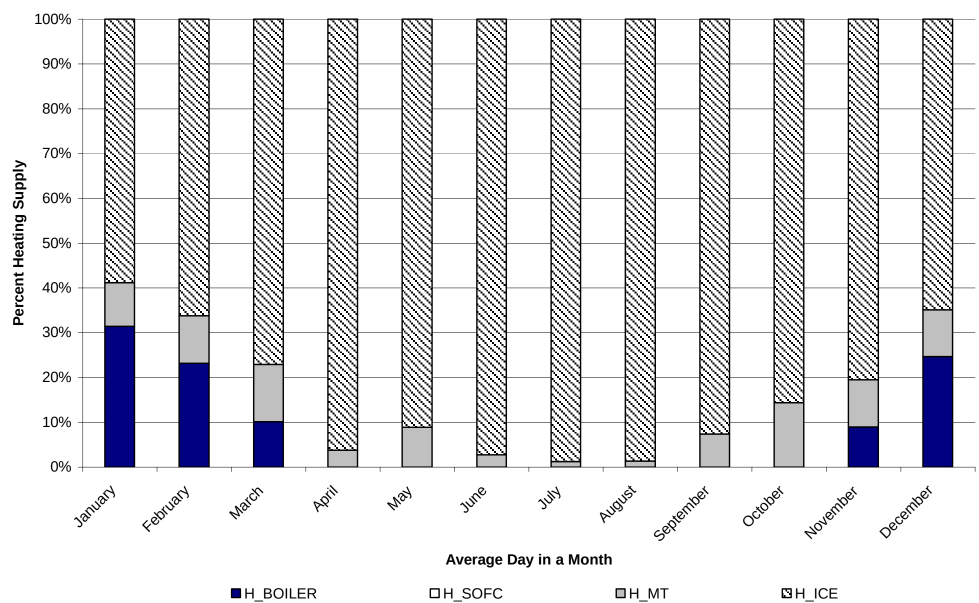



**Figure 5-40: Percent heating supply from energy systems: Hourly Model for min $SO_2$.**

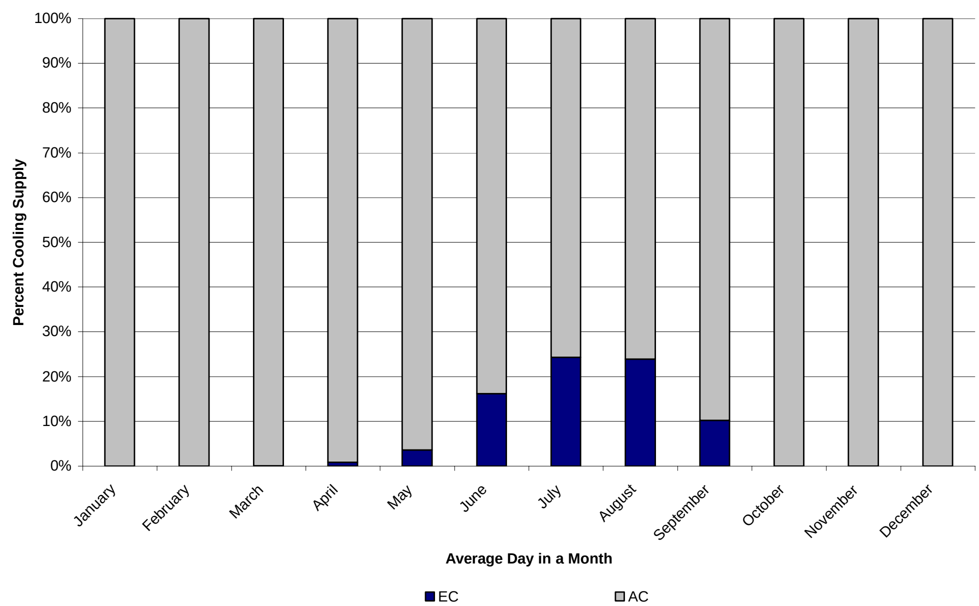



**Figure 5-41: Percent heating supply from energy systems: Hourly Model for min $SO_2$.**

When using the *Simplified Yearly LCA Optimization Model* to minimize $SO_2$ in the year, the results of the optimization model was generally similar to that obtained from the *Hourly LCA Optimization Model* for minimizing $SO_2$. Figures 5-42 and 5-43 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing $SO_2$, respectively. Figures 5-44 and 5-45 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing $SO_2$, respectively. Figures 5-46 and 5-47 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing $SO_2$, respectively. The graphs indicate the similarity in operational trends of the building.

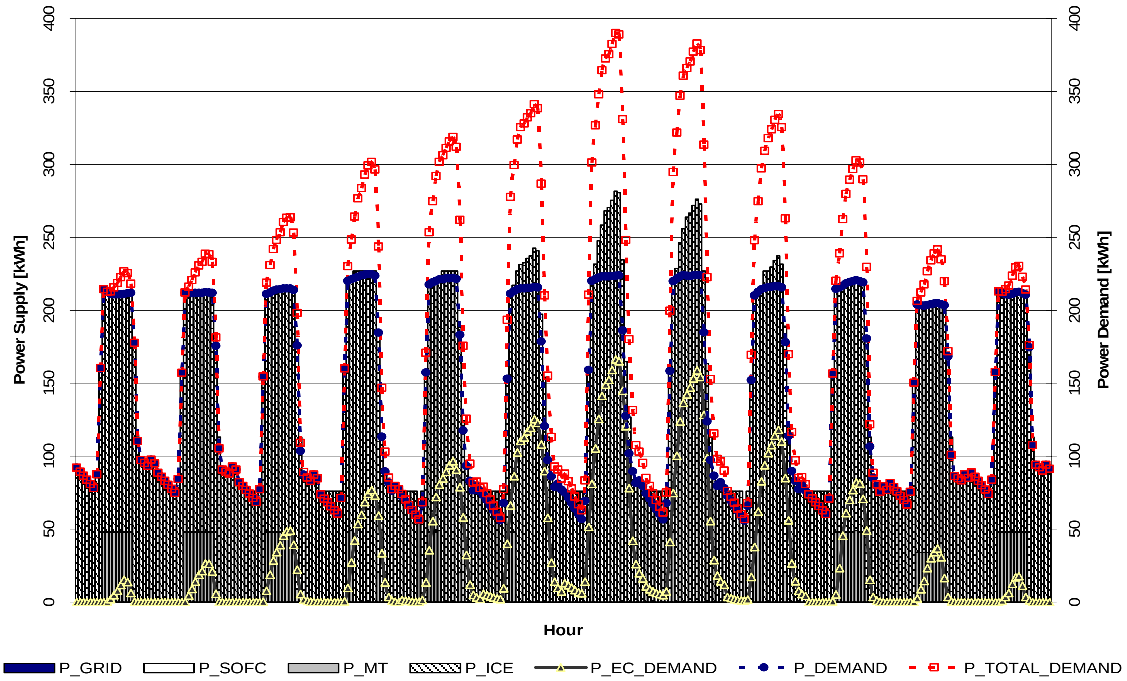



**Figure 5-42: Power supply: solution from Hourly Model for min $SO_2$.**

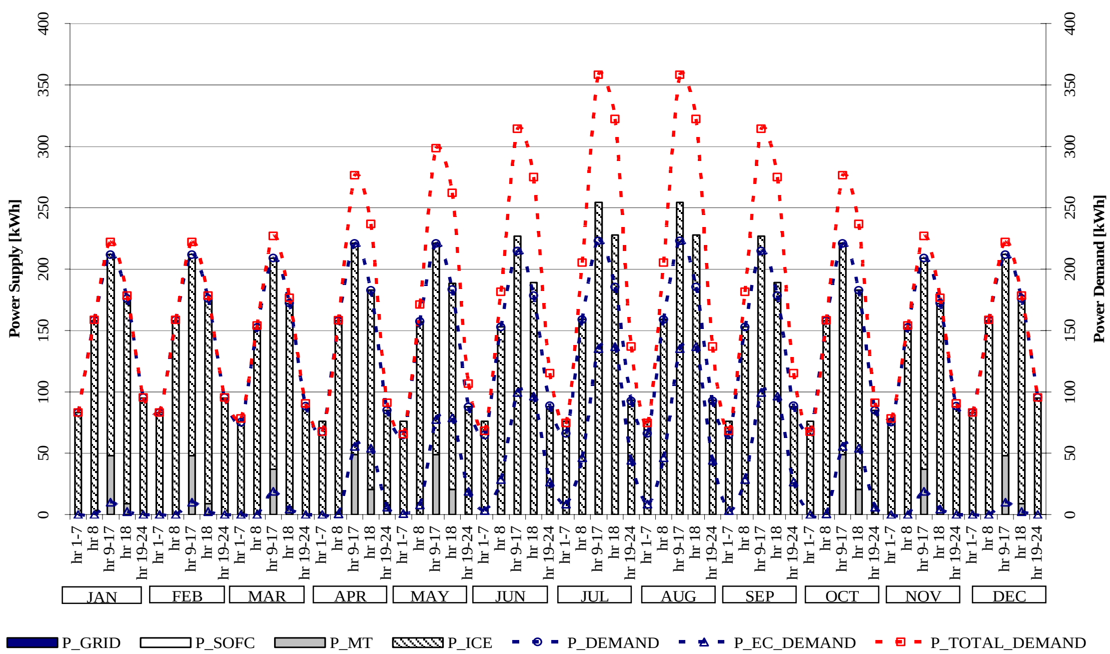



**Figure 5-43: Power supply: solution from Yearly Model for min $SO_2$.**

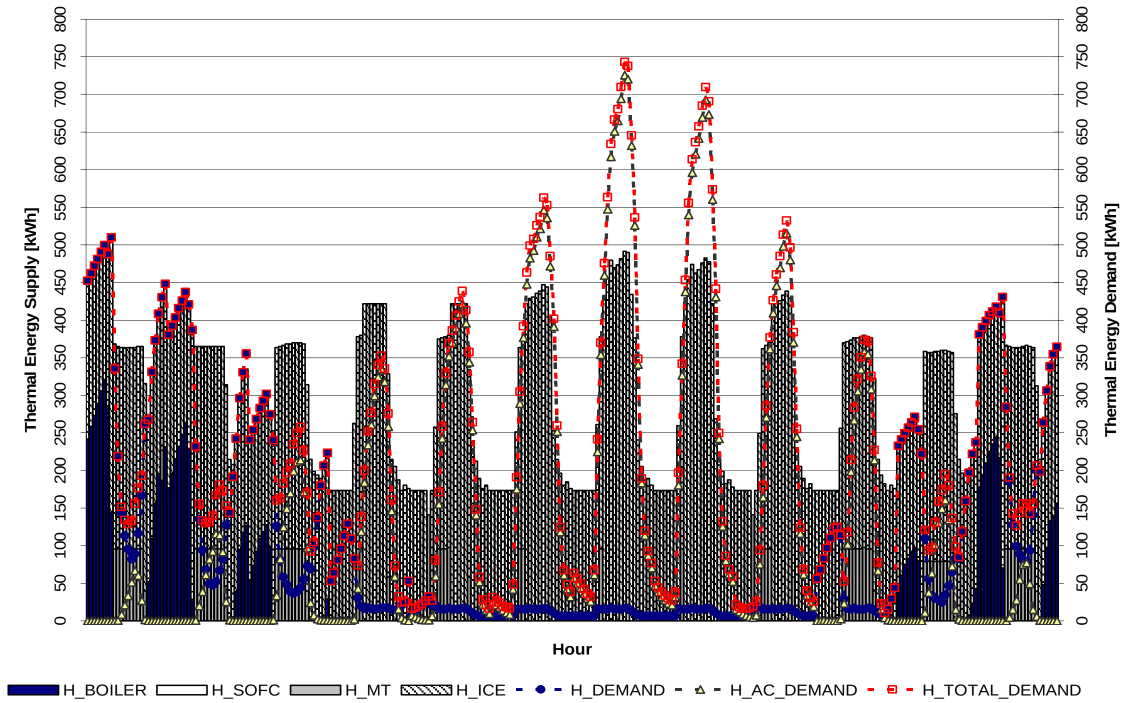



**Figure 5-44: Heating supply: solution from Hourly Model for min $SO_2$.**

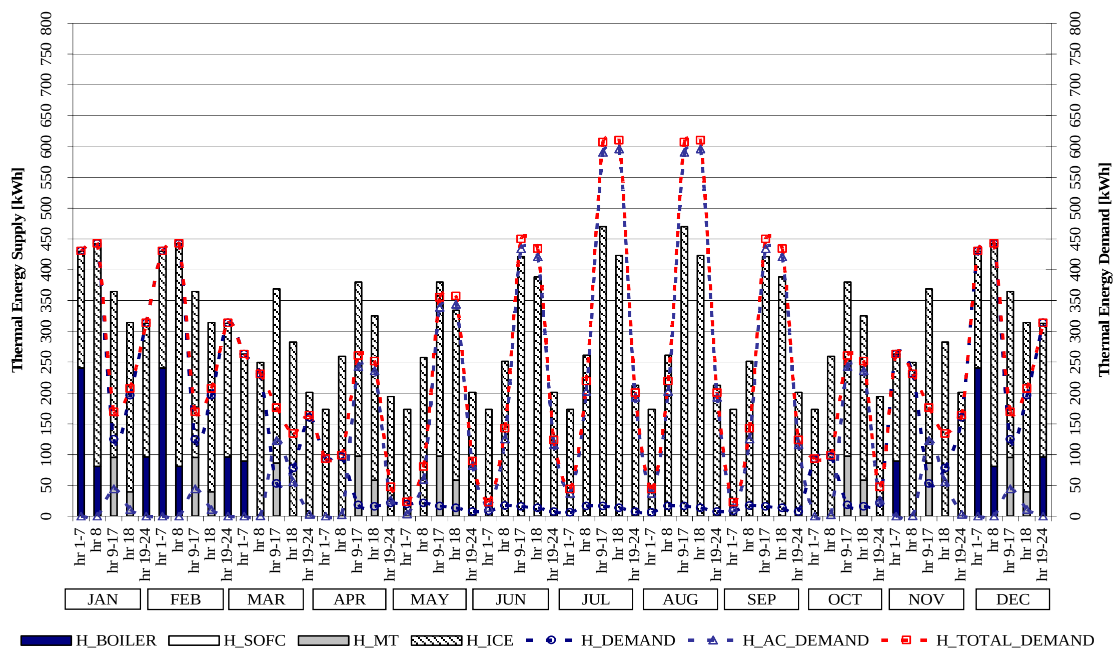



**Figure 5-45: Heating supply: solution from Yearly Model for min $SO_2$.**

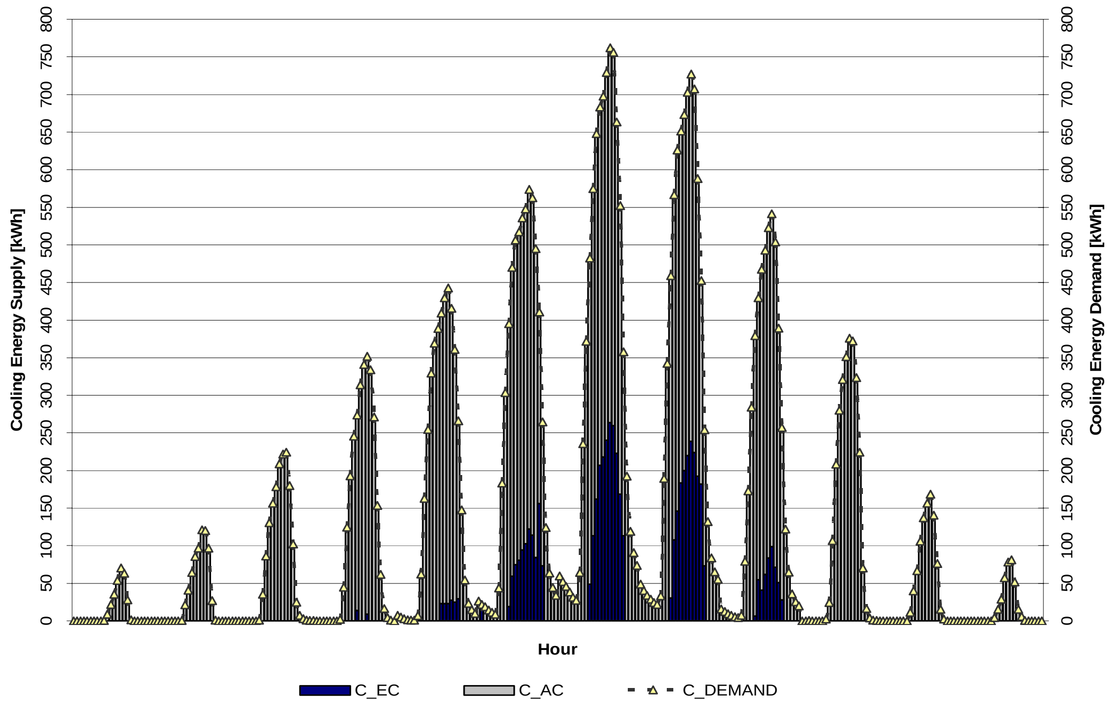



**Figure 5-46: Cooling supply: solution from Hourly Model for min $SO_2$.**

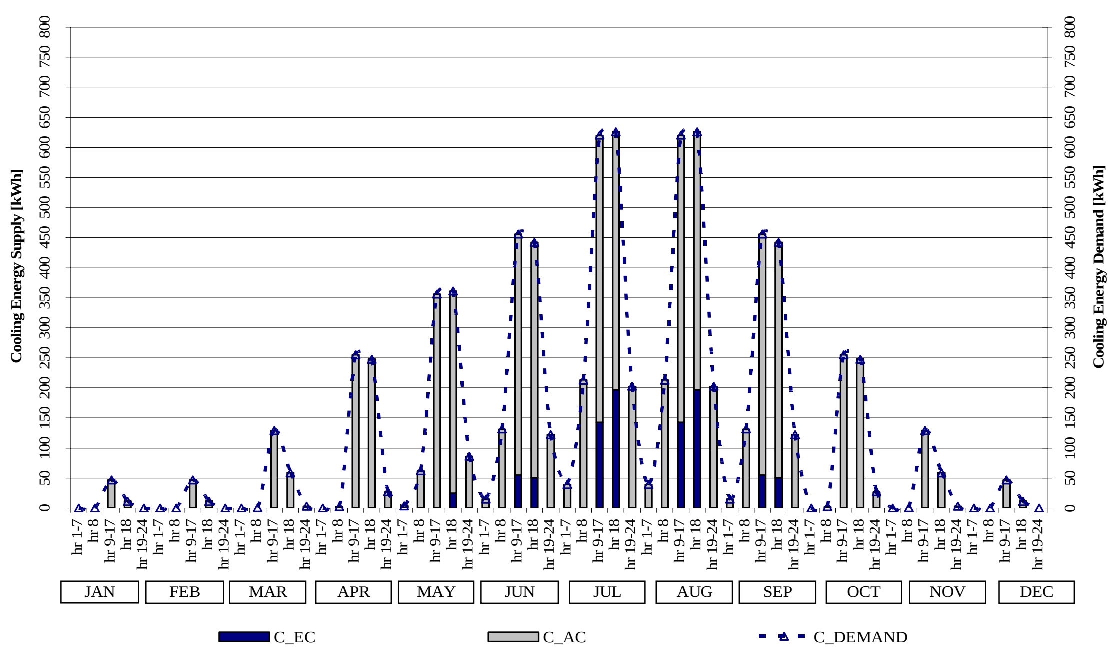



**Figure 5-47: Cooling supply: solution from Yearly LCA for min $SO_2$.**

When minimizing $SO_2$, the lowest values of the objective function (less than 10% of the maximum value) were attained in the transitional months of April, May, September, and October as well as November. The highest values of the objective function (greater than 60% of the maximum value) were obtained in the heating months of January, February, and December. The objective function values varied between 10% and 40% of the maximum value in the cooling months of June, July, and August as well as March. The trend exhibited reflected the energy systems in use; the highest values of the $SO_2$ objective function in the heating months were because the gas boiler was used to supplement the high thermal demand in addition to the cogenerated heat, whereas in the rest of the month the value of the objective function was relatively lower because no supplemental heat from the gas boiler was required and the cogenerated heat met the thermal and cooling demand. The objective function values showed an increase in value in the cooling months because of the relatively higher production of energy to meet the high cooling demand in those months. Figure 5-48 show the normalized objective function values of $SO_2$ in the 12 average days of January through December and the calculated values of the indicators corresponding to the minimum objective values. Table 5-13 shows the values of the $SO_2$ objective function and the corresponding indicator values.

The results obtained from the *Simplified Yearly LCA Optimization Model* generated the total value of the objective function and the corresponding values of the other indicators. Figure 5-49 shows the values of $SO_2$ expressed in *kg* corresponding to each objective function, respectively. Generally, when minimizing the $SO_2$, AP, NOx, TOPP and PE, the values of $SO_2$ obtained were approximately equal, but the values of the $SO_2$ increased about three times when minimizing GWP and $CO_2$, and about 48 times when minimizing cost. These trends reflect the characteristics of the energy systems used when minimizing each of the objective functions. Cogeneration systems have lower $SO_2$ emission factors compared to the average electric grid. Since cogeneration system were primarily used when minimizing $SO_2$, AP, NOx, TOPP and PE, the resultant $SO_2$ values obtained from the optimization problems were lower than those obtained when the average electric grid was used to meet the electric demand, as in the case when minimizing cost. Because the average electric grid was used partially to meet the electrical demand when minimizing GWP and $CO_2$, the resultant $SO_2$ was higher than that obtained from minimizing $SO_2$.

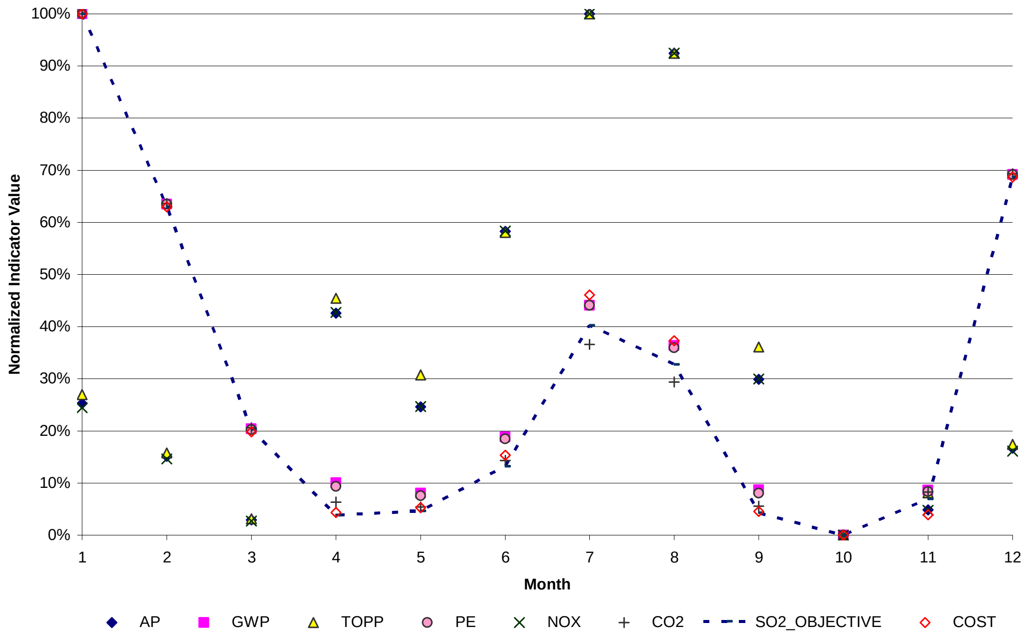
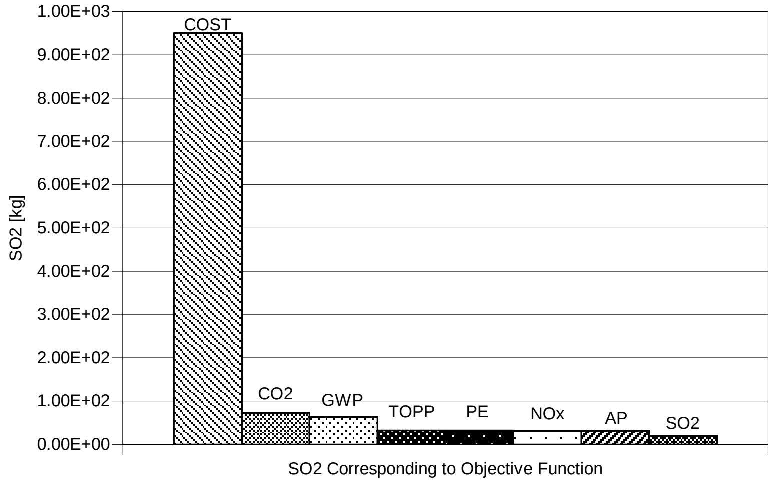



**Figure 5-48: Normalized indicator values corresponding to $SO_2$ objective function (Hourly Model).**

**Table 5-13: Indicator values corresponding to $SO_2$ objective function (Hourly Model).**

| | AP | GWP | TOPP | PE | $NO_X$ | $CO_2$ | $SO_2$ Objective | COST |
|---|---|---|---|---|---|---|---|---|
| January | 6.86E+00 | 3.12E+03 | 1.36E+01 | 1.58E+04 | 9.76E+00 | 2.84E+03 | 6.61E-02 | 5.67E+02 |
| February | 6.66E+00 | 2.81E+03 | 1.32E+01 | 1.43E+04 | 9.47E+00 | 2.55E+03 | 5.99E-02 | 5.20E+02 |
| March | 6.41E+00 | 2.45E+03 | 1.27E+01 | 1.25E+04 | 9.13E+00 | 2.20E+03 | 5.27E-02 | 4.65E+02 |
| April | 7.21E+00 | 2.36E+03 | 1.43E+01 | 1.20E+04 | 1.03E+01 | 2.08E+03 | 5.00E-02 | 4.45E+02 |
| May | 6.85E+00 | 2.35E+03 | 1.38E+01 | 1.20E+04 | 9.76E+00 | 2.07E+03 | 5.01E-02 | 4.47E+02 |
| June | 7.52E+00 | 2.44E+03 | 1.48E+01 | 1.24E+04 | 1.07E+01 | 2.15E+03 | 5.16E-02 | 4.59E+02 |
| July | 8.36E+00 | 2.65E+03 | 1.65E+01 | 1.35E+04 | 1.19E+01 | 2.33E+03 | 5.61E-02 | 4.98E+02 |
| August | 8.21E+00 | 2.58E+03 | 1.62E+01 | 1.31E+04 | 1.17E+01 | 2.27E+03 | 5.48E-02 | 4.87E+02 |
| September | 6.95E+00 | 2.35E+03 | 1.40E+01 | 1.20E+04 | 9.91E+00 | 2.07E+03 | 5.01E-02 | 4.46E+02 |
| October | 6.35E+00 | 2.28E+03 | 1.25E+01 | 1.17E+04 | 9.05E+00 | 2.03E+03 | 4.93E-02 | 4.40E+02 |
| November | 6.45E+00 | 2.35E+03 | 1.29E+01 | 1.20E+04 | 9.19E+00 | 2.10E+03 | 5.05E-02 | 4.45E+02 |
| December | 6.69E+00 | 2.86E+03 | 1.32E+01 | 1.45E+04 | 9.52E+00 | 2.59E+03 | 6.09E-02 | 5.27E+02 |
| Lowest Value | 6.35E+00 | 2.28E+03 | 1.25E+01 | 1.17E+04 | 9.05E+00 | 2.03E+03 | 4.93E-02 | 4.40E+02 |
| Highest Value | 8.36E+00 | 3.12E+03 | 1.65E+01 | 1.58E+04 | 1.19E+01 | 2.84E+03 | 6.61E-02 | 5.67E+02 |




| | *SO2 Corresponding to Objective Function* |
|---|---|
| *COST Objective* | *9.50E+02* |
| *CO2 Objective* | *7.32E+01* |
| *GWP Objective* | *6.25E+01* |
| *TOPP Objective* | *3.21E+01* |
| *PE Objective* | *3.15E+01* |
| *NOx Objective* | *3.12E+01* |
| *AP Objective* | *3.10E+01* |
| *SO2 Objective* | *1.97E+01* |

**Figure 5-49: Indicator values corresponding to $SO_2$ objective function (Yearly Model).**

#### 5.3.1.4 Minimizing Primary Energy Consumption

When using the *Hourly LCA Optimization Model* to minimize PE consumption in the 12 average days in the 12 months, the SOFC cogeneration system was used partially in the months of May through October to supply part of the power and thermal demands of the building. The remainder of the power and thermal requirements were supplied mainly by the ICE cogeneration system and to a lesser extent by the MT cogeneration system. That is because the SOFC has a relatively lower PE usage factor than the other systems and also because the heating requirement in those months were low. Therefore, the partial use of the SOFC system was higher in the cooling months than in the heating months (the SOFC has a higher power to heat ratio than the other cogeneration systems). When the heating demand was higher and cooling demand was low, as in the months of January, February, March, November and December, the ICE cogeneration system provided most of the power and thermal energy and the remaining power and heating demand was supplemented by the average electric grid and the gas boiler, respectively. The MT cogeneration system was used minimally in the months of March and November to supply part of the energy requirements. Figures 5-50, 5-51 and 5-52 show the percent power, heating and cooling supply, respectively, of the energy systems in the 12 average days in the months of January through December.

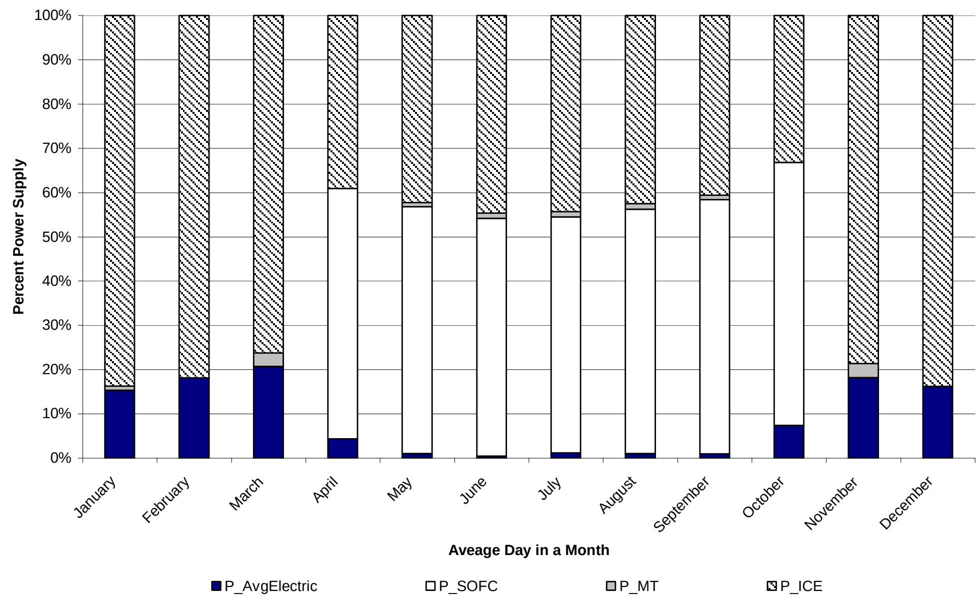



**Figure 5-50: Percent power supply from energy systems: Hourly Model for min PE.**

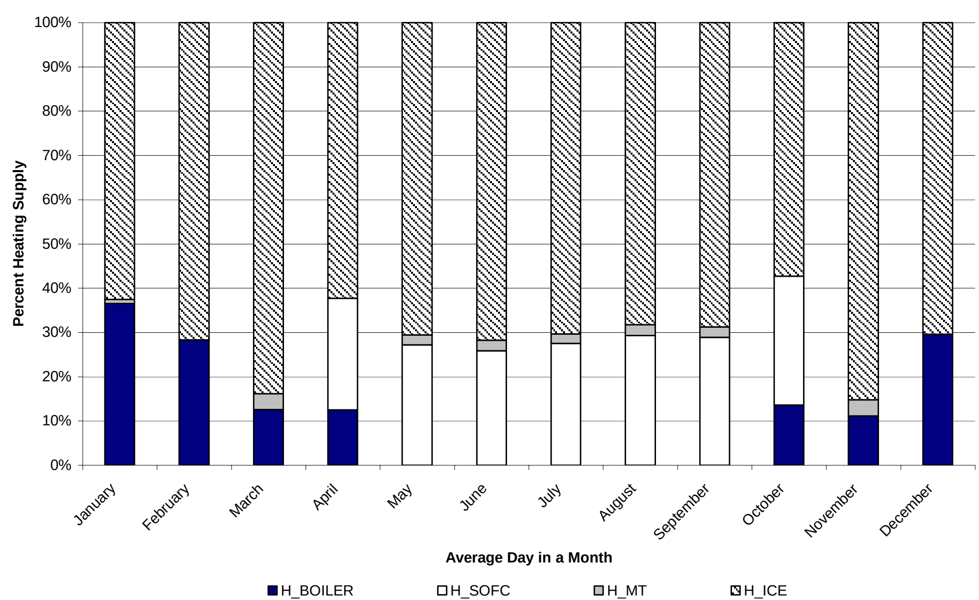



**Figure 5-51: Percent heating supply from energy systems: Hourly Model for min PE.**

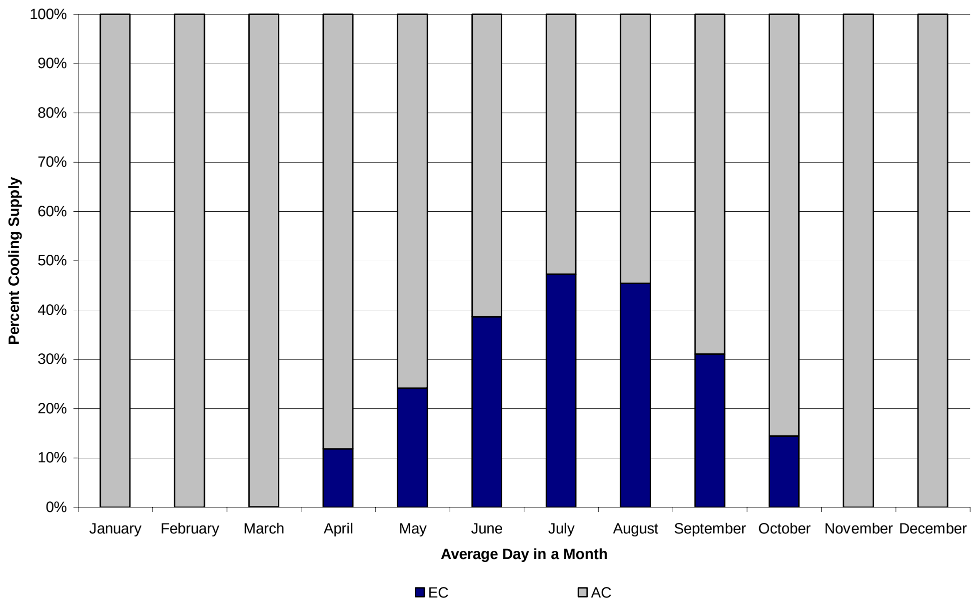



**Figure 5-52: Percent cooling supply from energy systems: Hourly Model for min PE.**

When using the *Simplified Yearly LCA Optimization Model* to minimize the PE in the year, the results were generally similar to those obtained from the *Hourly LCA Optimization Model.* The main difference in the results between the two models occurred in the heating months of January, February and December and the months of March and November, where electricity was mainly supplied by the ICE and SOFC cogeneration systems when using the *Simplified Yearly LCA Optimization Model*, whereas, when using the *Hourly LCA Optimization Model*, electricity was supplied mainly by the ICE and average electric grid in those months. This is mainly due to the aggregation in energy use data used in the *Simplified Yearly LCA Optimization Model.* When inspecting the Pareto optimal solutions for PE and cost using the *Simplified Yearly LCA Optimization Model*, it was found that there were no significant differences in the values of PE obtained at close to minimum PE. For example, a 0.9% decrease in PE value (from 4,506,060 to 4,461,200 kWh) resulted in a cost increase of only 7% (from $180,000 to $191,000). However, at the minimum PE value (4,461,200 kWh) the SOFC was in use whereas in the previous point (4,506,060 kWh) the SOFC was not in use while the average electric grid and ICE cogeneration systems were in use. Therefore, the approximation in data in the *Simplified Yearly LCA Optimization Model* resulted in different results than those obtained with the *Hourly LCA Optimization Model*.

Heating was supplied mainly by the gas boiler and the ICE cogeneration system and to a lesser extent by the SOFC in the heating months because of the relatively low thermal efficiency of the SOFC. As the thermal demand was lower in the months of April through October, heating was met by the ICE and the SOFC cogeneration systems. Cooling was supplied mainly by the absorption chiller and when the cooling demand was higher in the cooling months, the electric chiller was used to supply part of the cooling demand.

Figures 5-53 and 5-54 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and the *Simplified LCA Optimization Model* for minimizing PE, respectively. Figures 5-55 and 5-56 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified LCA Optimization Model* for minimizing PE, respectively. Figures 5-57 and 5-58 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and the *Simplified LCA Optimization Model* for minimizing PE, respectively. The graphs indicate the similarity in trends of the building.

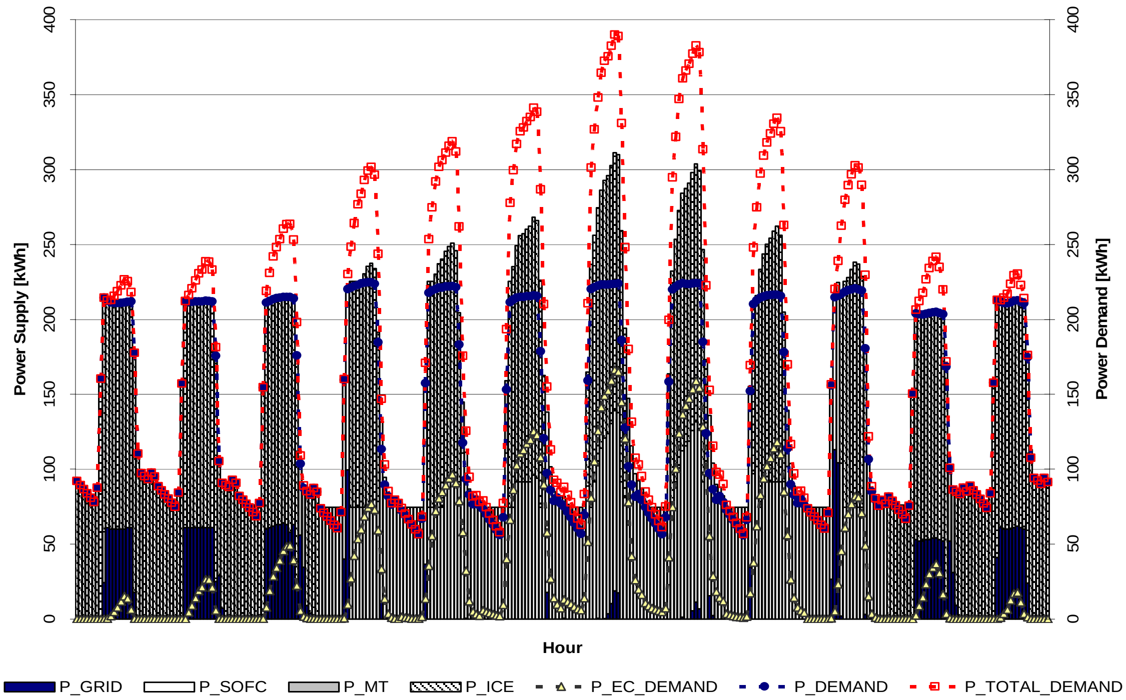



**Figure 5-53: Power supply: solution from Hourly Model for min PE.**

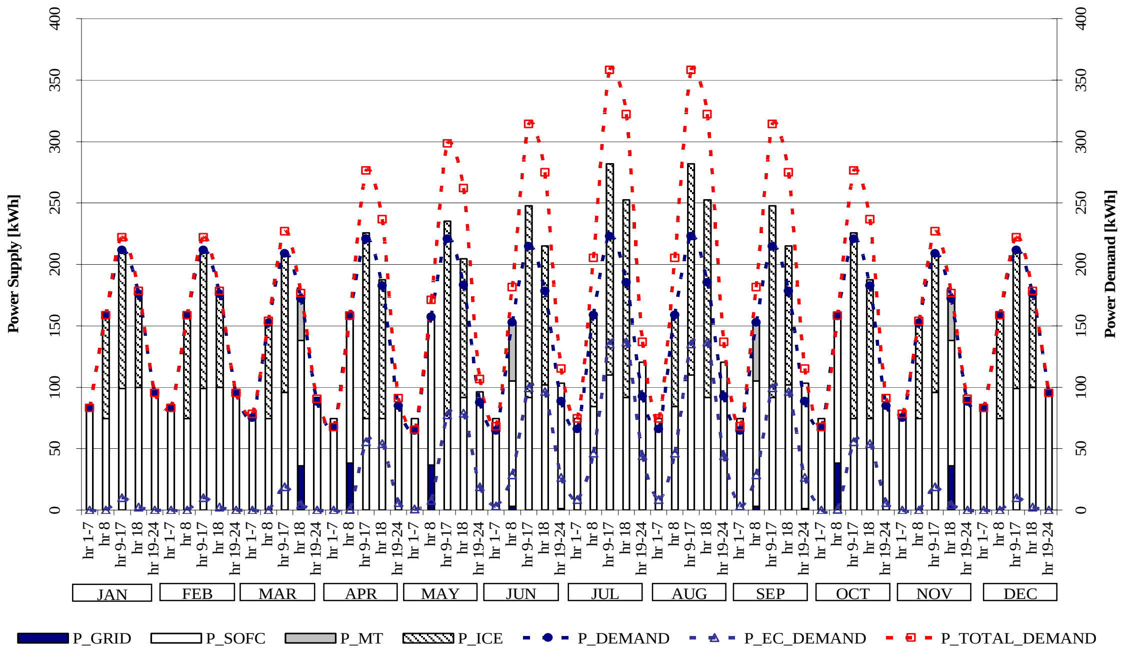



**Figure 5-54: Power supply: solution from Yearly Model for min PE.**

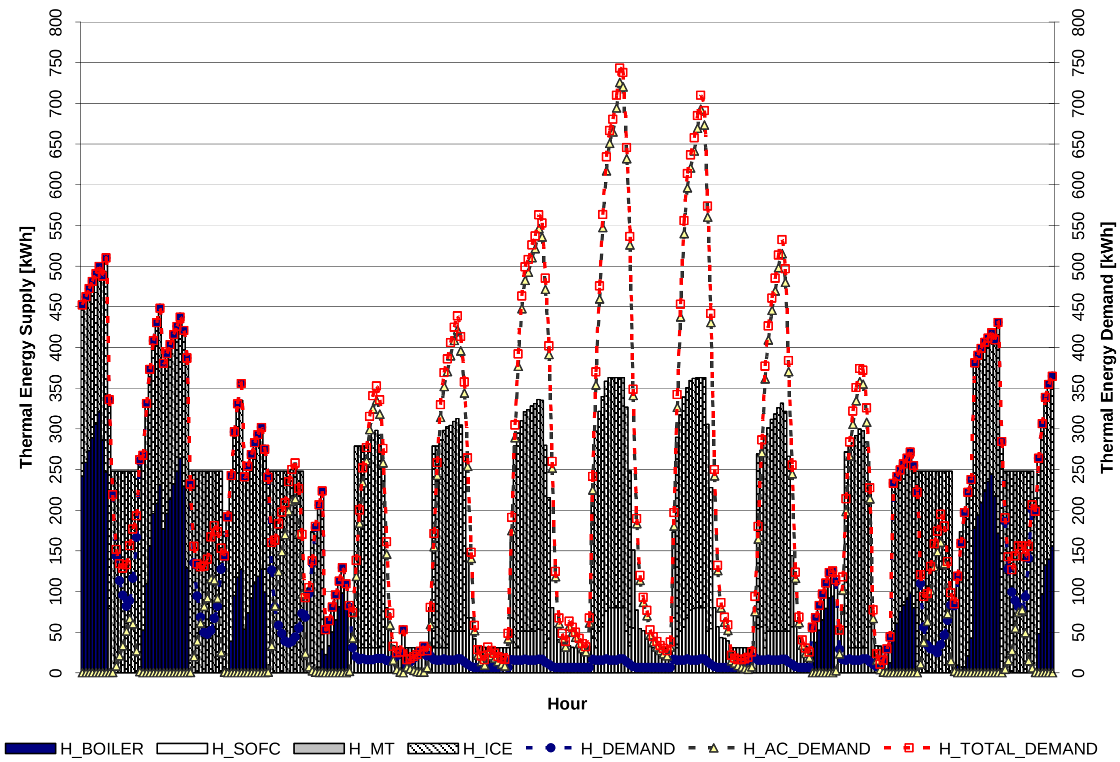



**Figure 5-55: Heating supply: solution from Hourly Model for min PE.**

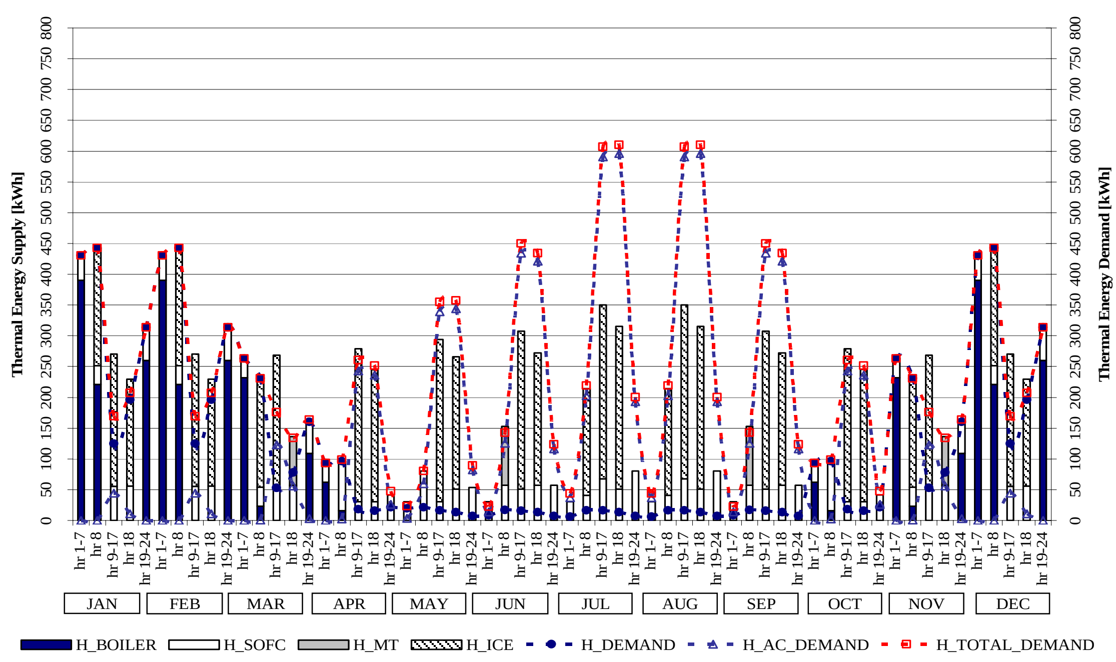



**Figure 5-56: Heating supply: solution from Yearly Model for min PE.**

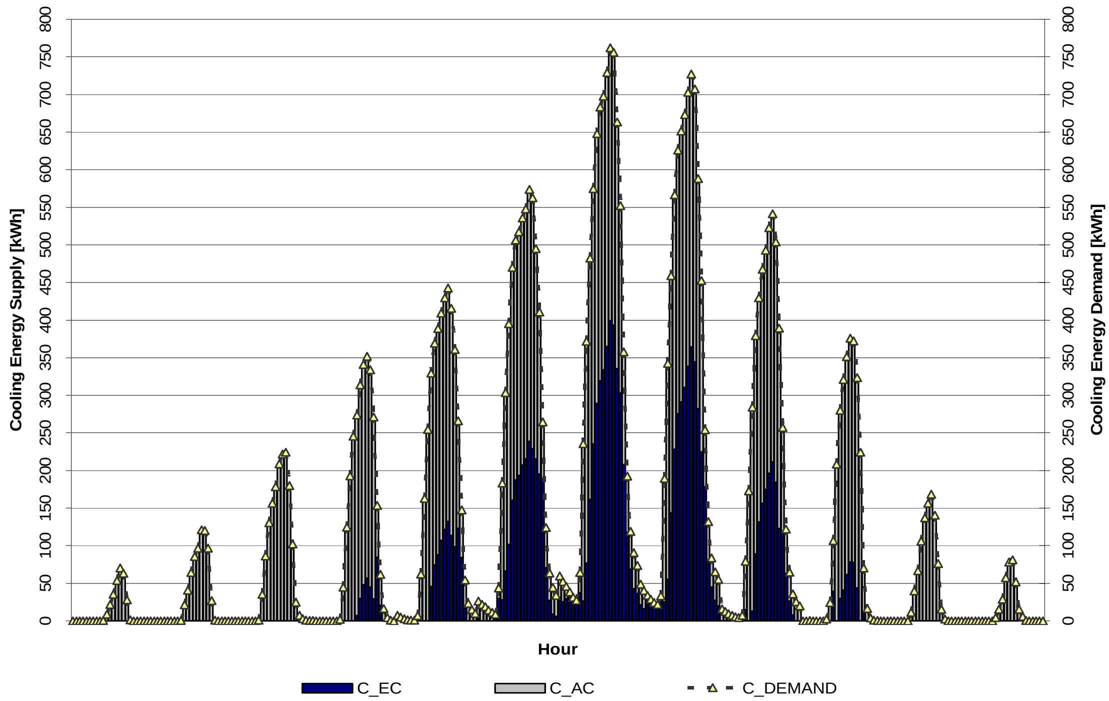



**Figure 5-57: Cooling supply: solution from Hourly Model for min PE.**

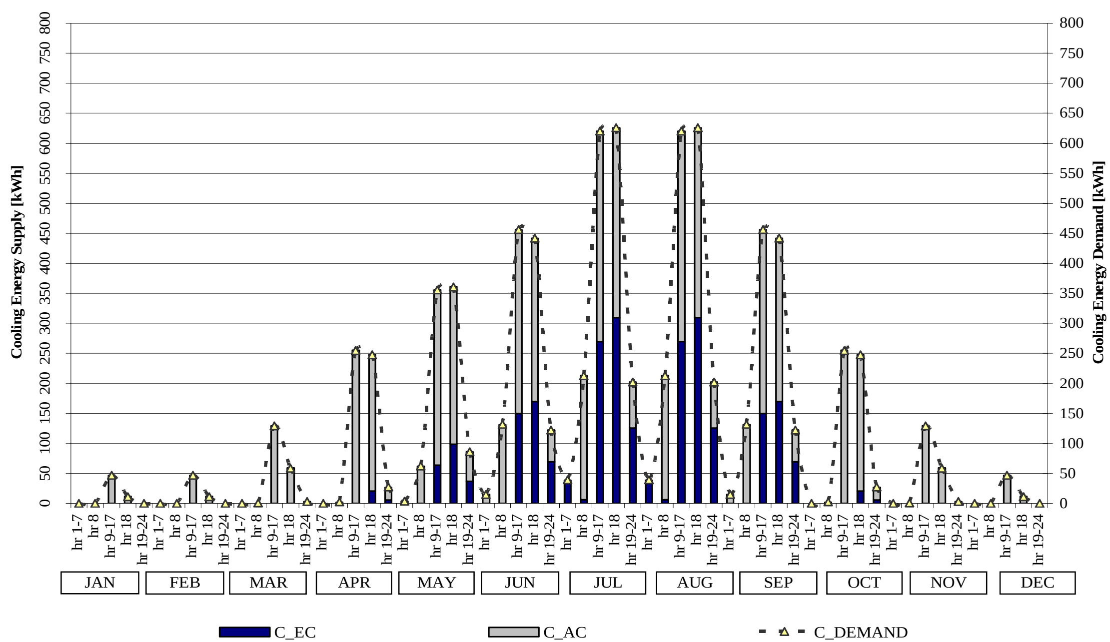



**Figure 5-58: Cooling supply: solution from Yearly Model for min PE.**

values to the minimum GWP value was very low. As the cost increased from 146,000 $ to 155,000 $, a 6% increase in cost, the GWP decreased from 1,250,000 kg of $CO_2$ equivalents to 948,000 kg of $CO_2$ equivalents, a 24% decrease in GWP; the power supply shifted gradually from the average electric grid as the main power supply to ICE cogeneration system with a decrease in the average electric grid use. The GWP values continued to decrease gradually as more of the power supply shifted from the average electric grid to the ICE and MT cogeneration systems up to the point when the cost was 160,000 $; after that point the GWP values plateau and the GWP value was further decreased by only 3% to the minimum GWP while the cost increased by an additional 12%, where most of the power was supplied by the ICE cogeneration system.

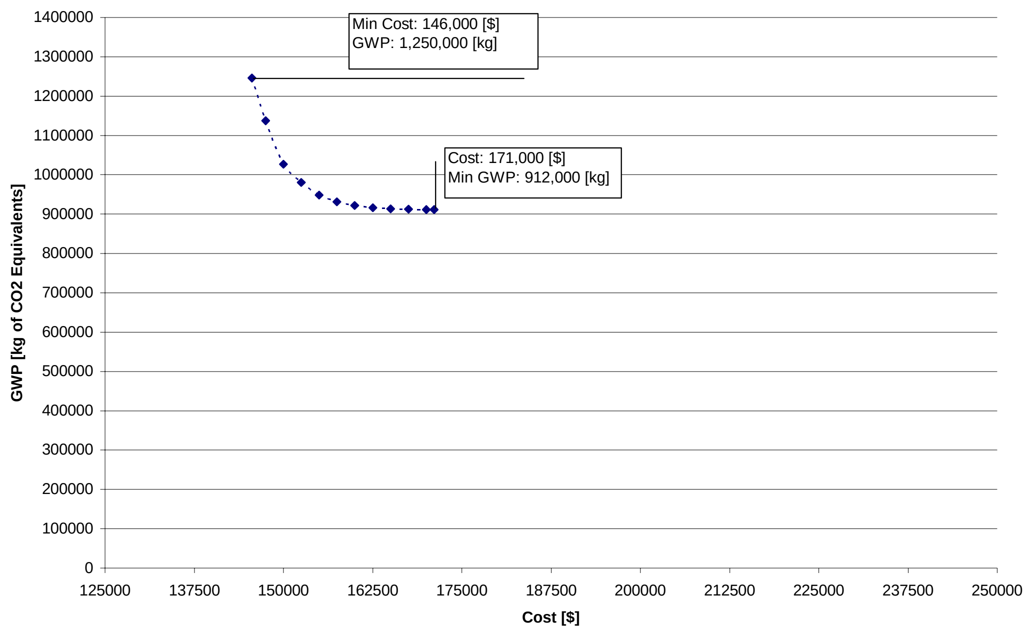



**Figure 5-72: Pareto optimal frontier for GWP and cost (Yearly Model).**

5-60 shows the values of PE in *kWh* corresponding to each objective function obtained from the *Simplified Yearly LCA Optimization Model* results. When minimizing the PE, $CO_2$, GWP and $SO_2$, the values of PE obtained were approximately in the same range (~+5% relative to PE), but the values of the PE increased by about 17% when minimizing TOPP, about 15% when minimizing cost and about 14% when minimizing $NO_x$ and AP.

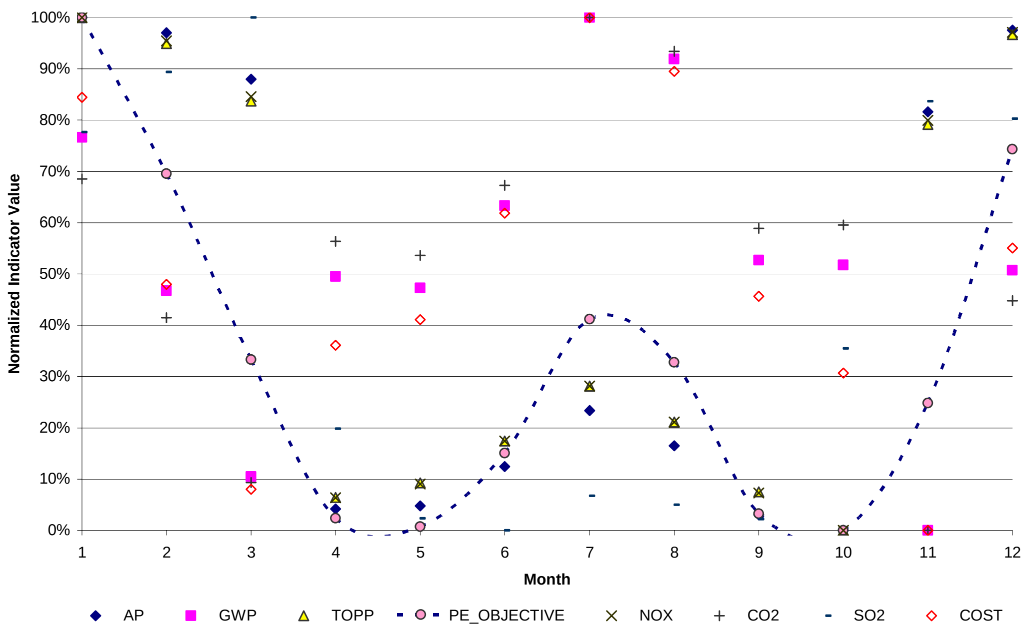
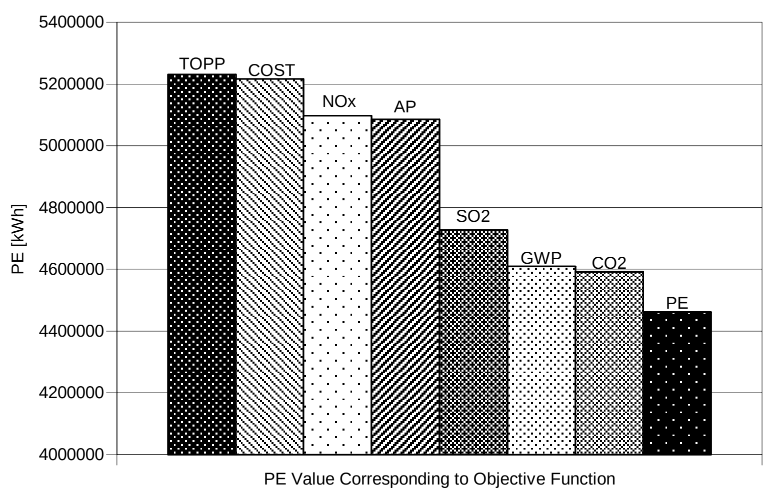



**Figure 5-59: Normalized indicator values corresponding to PE objective function (Hourly Model).**

**Table 5-14: Indicator values corresponding to PE objective function (Hourly Model).**

| | AP | GWP | TOPP | PE Objective | $NO_x$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 7.91E+00 | 3.15E+03 | 1.48E+01 | 1.54E+04 | 1.07E+01 | 2.86E+03 | 4.66E-01 | 5.26E+02 |
| February | 7.78E+00 | 2.85E+03 | 1.44E+01 | 1.38E+04 | 1.04E+01 | 2.58E+03 | 5.24E-01 | 4.74E+02 |
| March | 7.36E+00 | 2.49E+03 | 1.34E+01 | 1.20E+04 | 9.69E+00 | 2.24E+03 | 5.76E-01 | 4.17E+02 |
| April | 3.54E+00 | 2.87E+03 | 6.69E+00 | 1.04E+04 | 4.82E+00 | 2.73E+03 | 1.80E-01 | 4.57E+02 |
| May | 3.57E+00 | 2.85E+03 | 6.94E+00 | 1.03E+04 | 4.99E+00 | 2.70E+03 | 9.26E-02 | 4.64E+02 |
| June | 3.92E+00 | 3.01E+03 | 7.64E+00 | 1.11E+04 | 5.51E+00 | 2.85E+03 | 8.13E-02 | 4.94E+02 |
| July | 4.42E+00 | 3.38E+03 | 8.57E+00 | 1.24E+04 | 6.18E+00 | 3.19E+03 | 1.14E-01 | 5.49E+02 |
| August | 4.10E+00 | 3.30E+03 | 7.96E+00 | 1.20E+04 | 5.74E+00 | 3.13E+03 | 1.06E-01 | 5.34E+02 |
| September | 3.49E+00 | 2.91E+03 | 6.78E+00 | 1.05E+04 | 4.88E+00 | 2.76E+03 | 9.20E-02 | 4.71E+02 |
| October | 3.35E+00 | 2.90E+03 | 6.13E+00 | 1.03E+04 | 4.42E+00 | 2.77E+03 | 2.57E-01 | 4.49E+02 |
| November | 7.08E+00 | 2.38E+03 | 1.30E+01 | 1.16E+04 | 9.41E+00 | 2.14E+03 | 4.95E-01 | 4.05E+02 |
| December | 7.80E+00 | 2.89E+03 | 1.45E+01 | 1.41E+04 | 1.05E+01 | 2.61E+03 | 4.79E-01 | 4.84E+02 |
| Lowest Value | 3.35E+00 | 2.38E+03 | 6.13E+00 | 1.03E+04 | 4.42E+00 | 2.14E+03 | 8.13E-02 | 4.05E+02 |
| Highest Value | 7.91E+00 | 3.38E+03 | 1.48E+01 | 1.54E+04 | 1.07E+01 | 3.19E+03 | 5.76E-01 | 5.49E+02 |




| | *PE Value Corresponding to Objective Function* |
|---|---|
| *TOPP Objective* | *5231010* |
| *COST Objective* | *5216010* |
| *NOx Objective Value* | *5096630* |
| *AP Objective* | *5084870* |
| *SO2 Objective* | *4728020* |
| *GWP Objective* | *4610000* |
| *CO2 Objective* | *4592840* |
| *PE Objective* | *4461200* |

**Figure 5-60: Indicator values corresponding to PE objective function (Yearly Model).**

#### 5.3.1.5 Minimizing Cost

When using the *Hourly LCA Optimization Model* to minimize cost, the results of the optimization model showed that the average electric grid was used primarily to meet the electrical demand of the building and the ICE cogeneration system was used partially in the heating months of January, February and December as well as in March and November to meet part of the electrical demand. This is because of the high thermal demand in those months. Therefore, the cogenerated heat from the ICE system was used to meet part of the thermal demand; the remaining thermal demand was supplied by the gas boiler. In the average days of April through October, the thermal demand was supplied entirely by the gas boiler. The cooling demand was supplied primarily by the electric chiller and partially by the absorption chiller in the months corresponding to the ICE cogeneration system use. Figures 5-61, 5-62 and 5-63 show the percent power, heating and cooling supply, respectively of the energy systems in the 12 average days in the months of January through December.

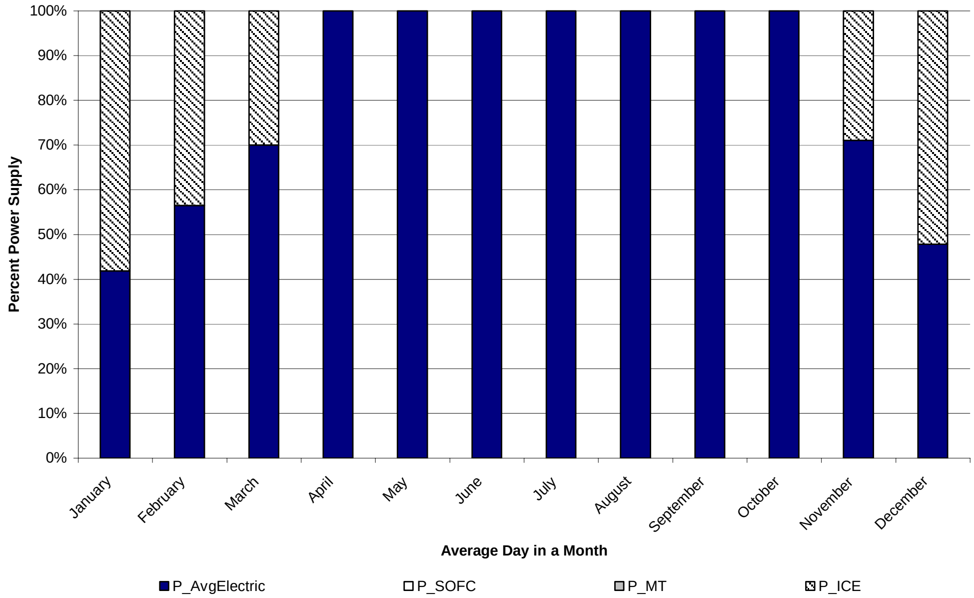



**Figure 5-61: Percent power supply from energy systems: Hourly Model for min cost.**

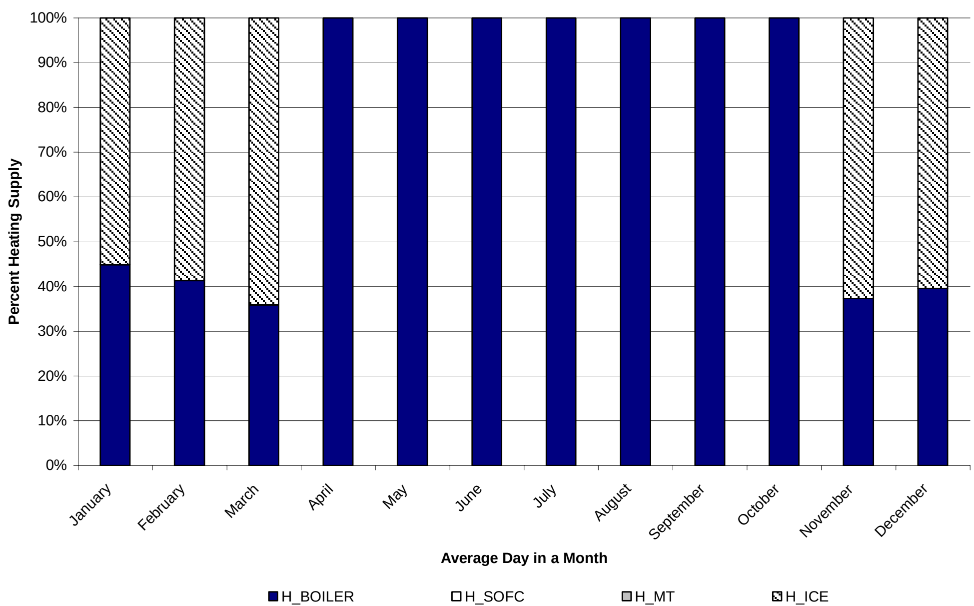



**Figure 5-62: Percent heating supply from energy systems: Hourly Model for min cost.**

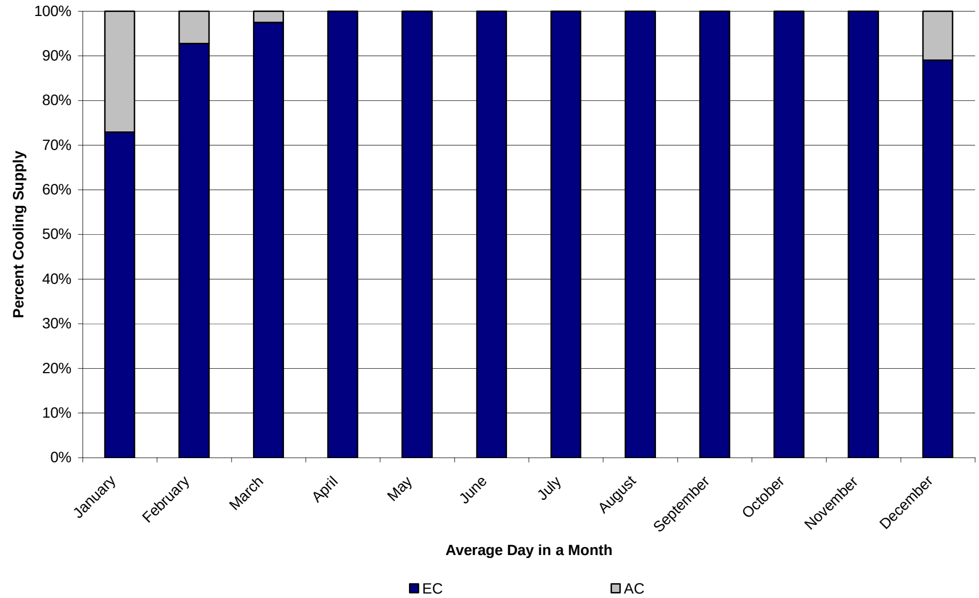



**Figure 5-63: Percent cooling supply from energy systems: Hourly Model for min cost.**

The results obtained from the *Simplified Yearly LCA Optimization Model* from minimizing cost in the year were similar to those obtained from the Hourly LCA Optimization Model for minimizing LCA. Figures 5-64 and 5-65 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization Model* for minimizing cost, respectively. Figures 5-66 and 5-67 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing cost, respectively. Figure 5-68 and 5-69 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization Model* for minimizing cost, respectively. The graphs indicate the similarity in operational trends of the building.

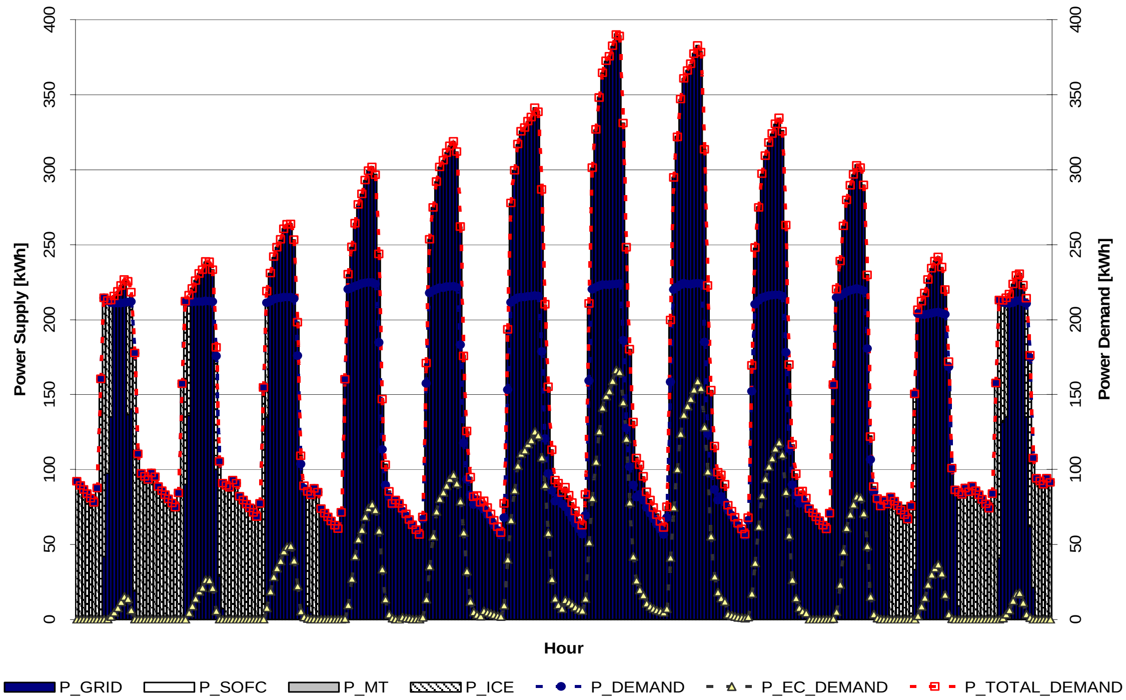



**Figure 5-64: Power supply: solution from Hourly Model for min cost.**

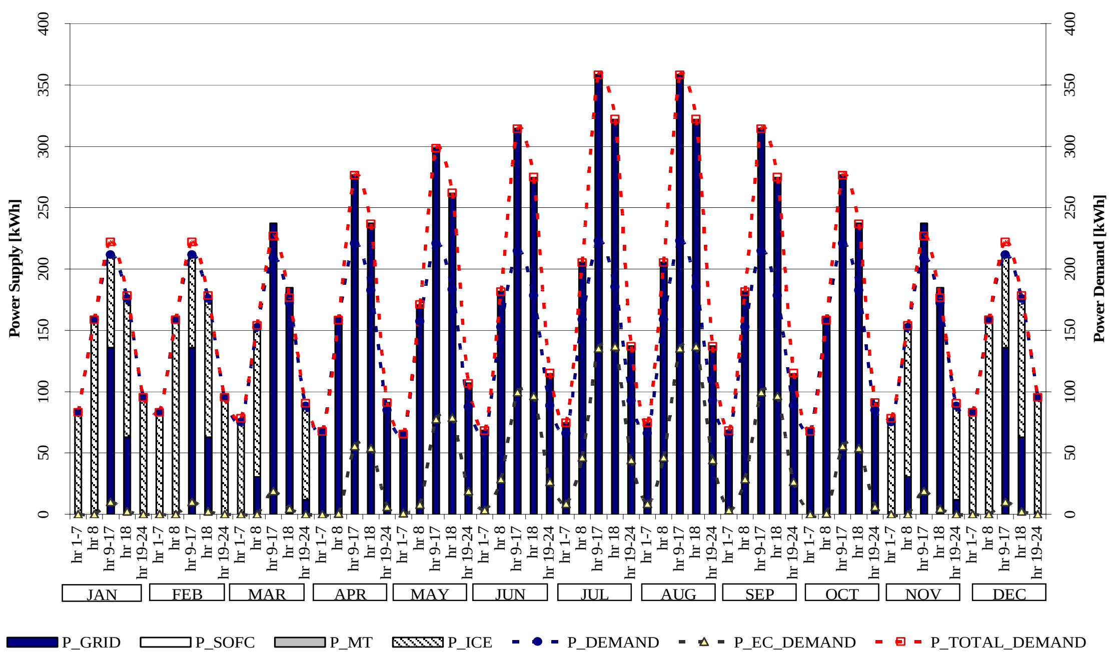



**Figure 5-65: Power supply: solution from Yearly Model for min cost.**

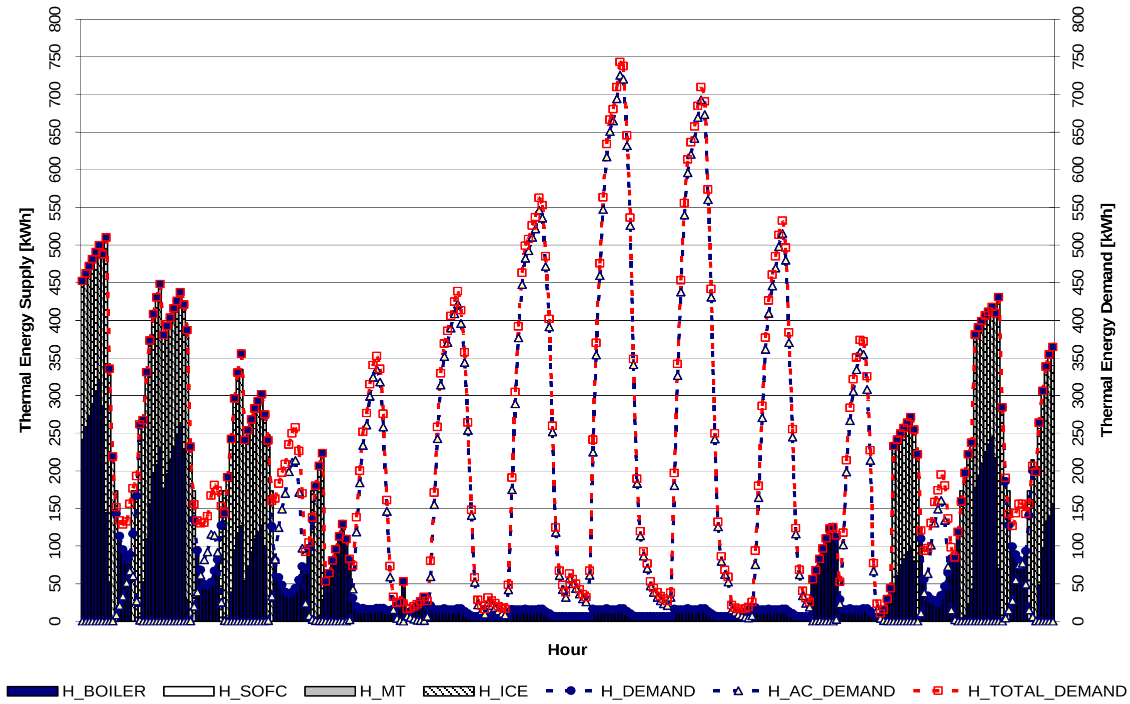



**Figure 5-66: Heating supply: solution from Hourly Model for min cost.**

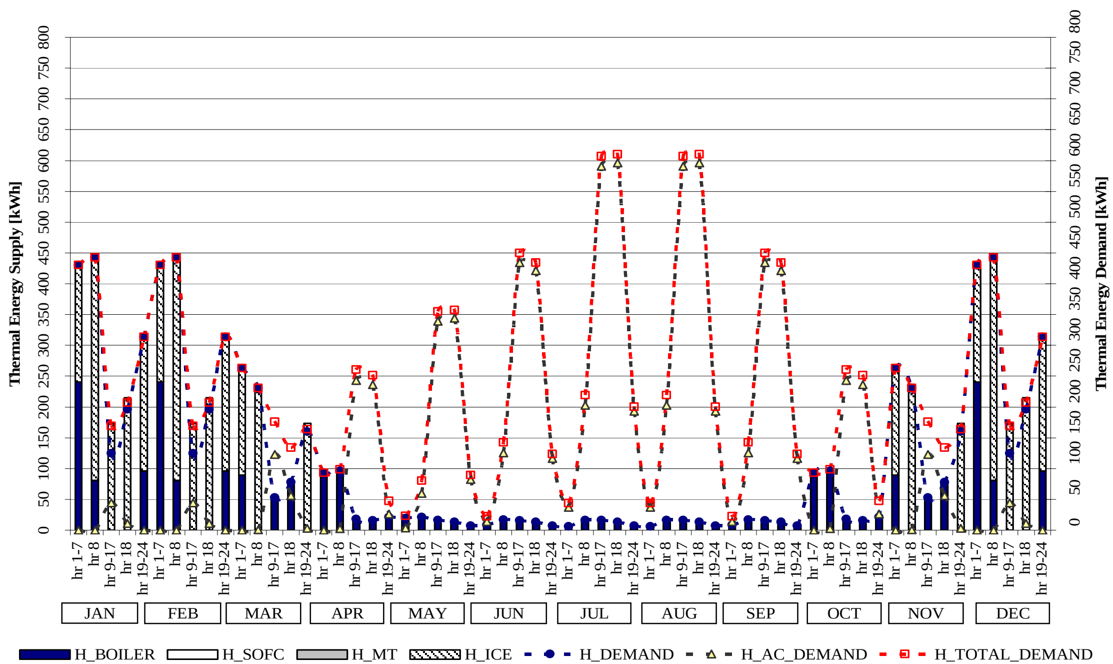



**Figure 5-67: Heating supply: solution from Yearly Model for min cost.**

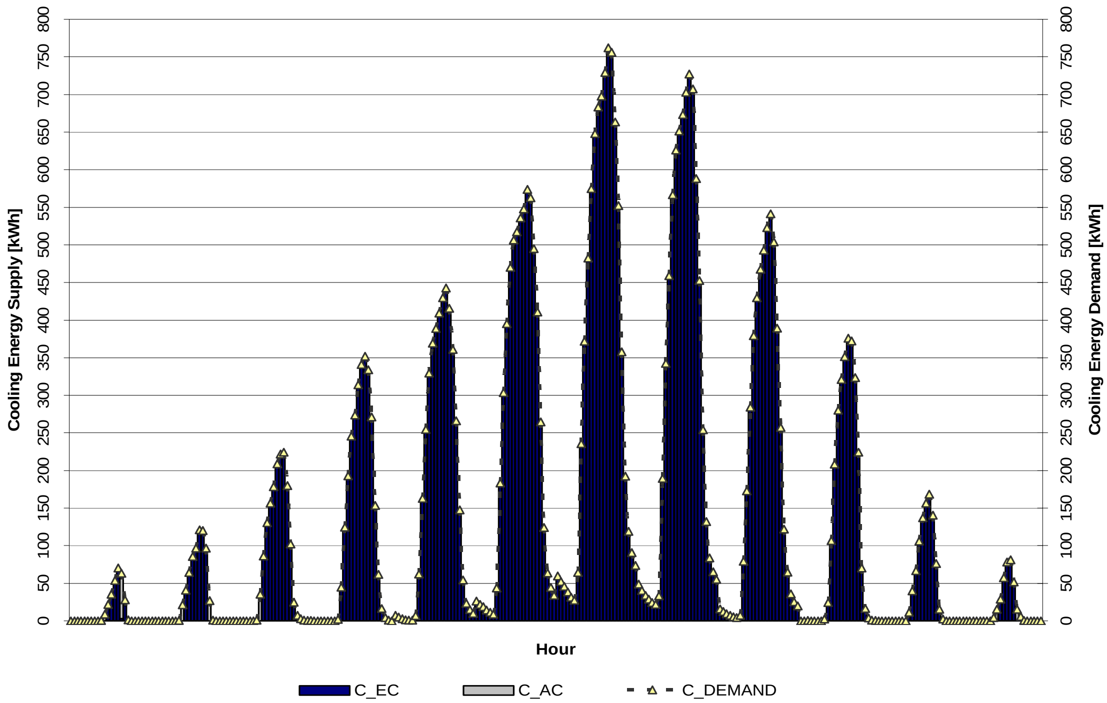



**Figure 5-68: Cooling supply: solution from Hourly Model for min cost.**

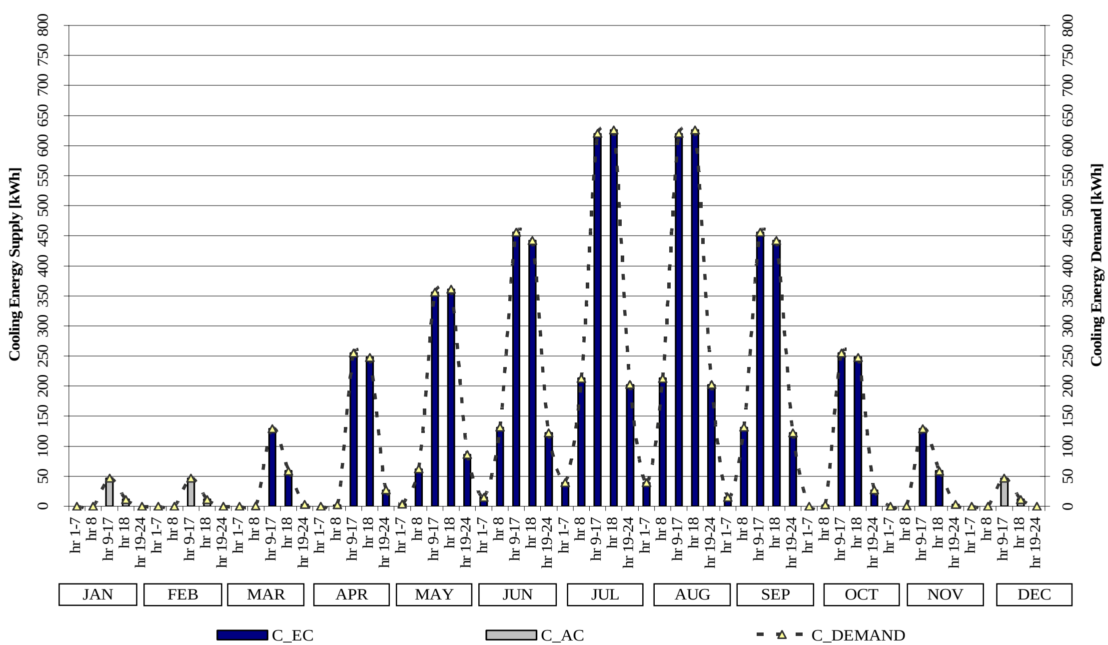



**Figure 5-69: Cooling supply: solution from Yearly Model for min cost.**

When minimizing cost using the *Hourly LCA Optimization Model*, the trend in the objective values throughout the 12 days was similar to that exhibited by the other indicators: the value of the objective function was highest in the average day in January, decreased to low values in April and May, increased again in July, decreased from July to the lowest value in October, and increased in November to a high value in December, as shown in Figure 5-70. Table 5-15 shows the indicator values corresponding to the cost objective in the 12 days in the 12 months. The increase in cost indicator values in January was due to the use of the ICE cogeneration system to supply part of the electrical demand the remaining was supplied by the average electric grid. In October, the value of the objective function was low because all of the electric demand was supplied by the average electric grid. The cost factor for the ICE cogeneration was relatively higher than the cost factor of the average electric grid, an average of \$0.128 and \$0.0788, respectively.

Generally, when minimizing cost, the corresponding values of the other indicators do not follow the same trend as that exhibited by the objective values throughout the 12 days. On the contrary, the values of the other indicators reflect the characteristics of the energy systems that were in use. For instance, the values of the other indicators corresponding to the values of the objective function exhibited the same trend, where their values increase when the average electric grid use was high and were lower when partial of the energy demand was met by the ICE cogeneration system. Generally, the values of the other indicators reach the peak when the electric demand was highest in the cooling month because the high cooling demand was met by the electric chiller using electricity from the average electric grid.

The results obtained from the *Simplified Yearly LCA Optimization Model* generated the total values of the objective function and the corresponding values of the other indicators. Figure 5-71 shows the values of cost in *\$* corresponding to each objective function. Generally, when minimizing cost, $CO_2$, GWP, and $SO_2$, the values of cost obtained were approximately in the same range, but the values of cost increased about 30% when minimizing PE and up to 64% when minimizing TOPP, AP and $NO_x$. These trends reflect the cost factors of the energy systems used when minimizing each of the objective functions. For instance, the cost of using mainly ICE and partially MT cogeneration systems to meet the power and thermal demand when minimizing GWP and $CO_2$ was only 17% higher than the cost of using the average electric grid primarily when minimizing cost. When comparing these results to the reduction in emissions that could be achieved when minimizing GWP versus cost, the benefits might outweigh the cost. The increase in cost observed when minimizing PE, TOPP, AP, and NOx was mainly due to the increase in use of the cogeneration systems, which have higher cost factors than the average electric grid.

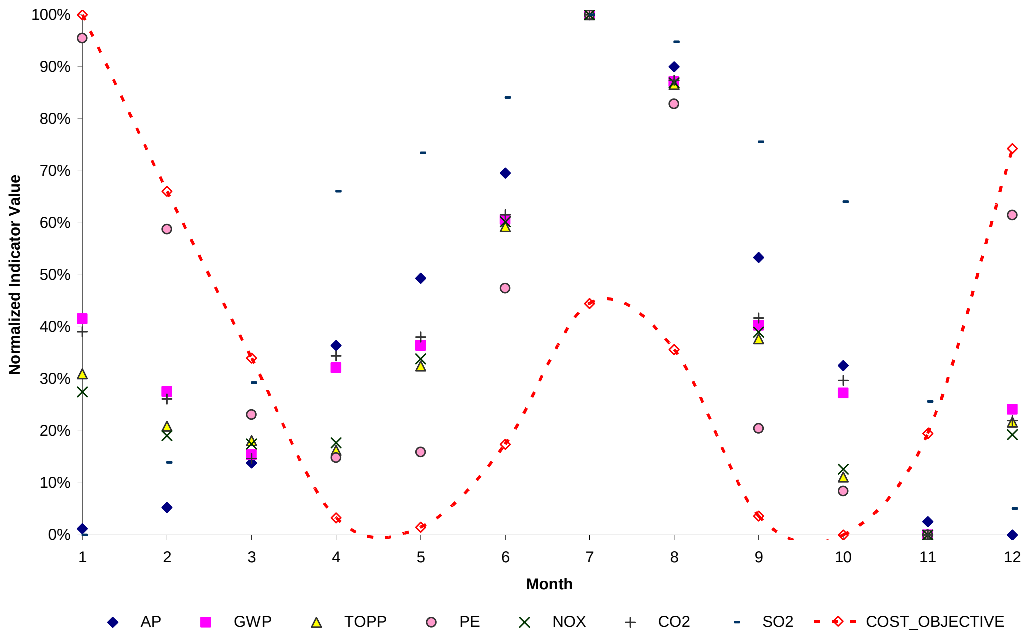
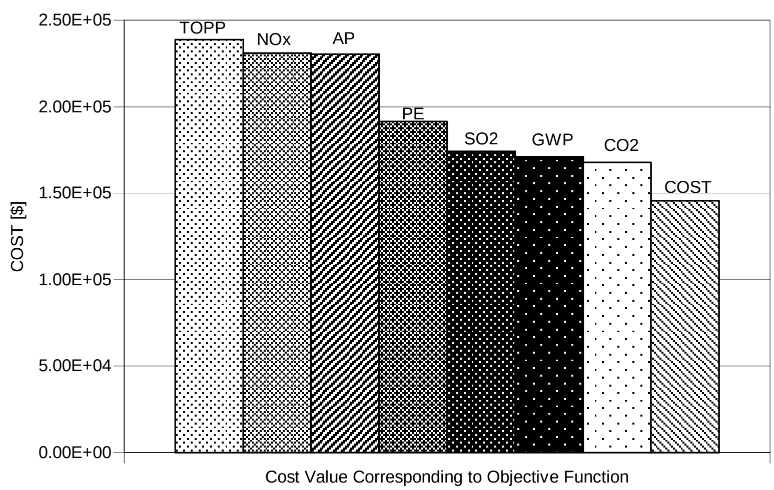



**Figure 5-70: Normalized indicator values corresponding to cost objective function (Hourly Model).**

**Table 5-15: Indicator values corresponding to cost (Hourly Model).**

| | AP | GWP | TOPP | $NO_X$ | $CO_2$ | $SO_2$ | COST Objective | PE |
|---|---|---|---|---|---|---|---|---|
| January | 8.62E+00 | 3.46E+03 | 1.46E+01 | 1.06E+01 | 3.20E+03 | 1.18E+00 | 5.13E+02 | 1.62E+04 |
| February | 8.82E+00 | 3.30E+03 | 1.41E+01 | 1.03E+01 | 3.05E+03 | 1.58E+00 | 4.55E+02 | 1.49E+04 |
| March | 9.25E+00 | 3.16E+03 | 1.39E+01 | 1.02E+01 | 2.92E+03 | 2.01E+00 | 4.01E+02 | 1.37E+04 |
| April | 1.04E+01 | 3.35E+03 | 1.39E+01 | 1.02E+01 | 3.15E+03 | 3.07E+00 | 3.48E+02 | 1.34E+04 |
| May | 1.10E+01 | 3.40E+03 | 1.47E+01 | 1.08E+01 | 3.19E+03 | 3.28E+00 | 3.45E+02 | 1.34E+04 |
| June | 1.20E+01 | 3.69E+03 | 1.60E+01 | 1.18E+01 | 3.45E+03 | 3.58E+00 | 3.72E+02 | 1.45E+04 |
| July | 1.36E+01 | 4.15E+03 | 1.80E+01 | 1.33E+01 | 3.88E+03 | 4.03E+00 | 4.18E+02 | 1.63E+04 |
| August | 1.31E+01 | 4.00E+03 | 1.74E+01 | 1.28E+01 | 3.74E+03 | 3.88E+00 | 4.03E+02 | 1.57E+04 |
| September | 1.12E+01 | 3.45E+03 | 1.49E+01 | 1.10E+01 | 3.23E+03 | 3.34E+00 | 3.49E+02 | 1.36E+04 |
| October | 1.02E+01 | 3.30E+03 | 1.36E+01 | 1.00E+01 | 3.09E+03 | 3.01E+00 | 3.42E+02 | 1.32E+04 |
| November | 8.69E+00 | 2.98E+03 | 1.30E+01 | 9.54E+00 | 2.76E+03 | 1.91E+00 | 3.76E+02 | 1.29E+04 |
| December | 8.56E+00 | 3.26E+03 | 1.41E+01 | 1.03E+01 | 3.01E+03 | 1.32E+00 | 4.69E+02 | 1.50E+04 |
| Lowest Value | 8.56E+00 | 2.98E+03 | 1.30E+01 | 9.54E+00 | 2.76E+03 | 1.18E+00 | 3.42E+02 | 1.29E+04 |
| Highest Value | 1.36E+01 | 4.15E+03 | 1.80E+01 | 1.33E+01 | 3.88E+03 | 4.03E+00 | 5.13E+02 | 1.63E+04 |




| | *Cost Value Corresponding to Objective Function* |
|---|---|
| *TOPP Objective* | *2.39E+05* |
| *NOx Objective* | *2.31E+05* |
| *AP Objective* | *2.30E+05* |
| *PE Objective* | *1.91E+05* |
| *SO2 Objective* | *1.74E+05* |
| *GWP Objective* | *1.71E+05* |
| *CO2 Objective* | *1.68E+05* |
| *COST Objective* | *1.46E+05* |

**Figure 5-71: Indicator values corresponding to cost (Yearly Model).**

#### 5.3.1.6 Pareto Optimal Solutions for Environmental Indicators & Cost

When analyzing the results obtained from the *Simplified Yearly LCA Optimization Model*, for minimizing GWP and cost objective functions, the minimum GWP objective function value was 912,000 kg of $CO_2$ equivalents and the cost required to achieve that value was 171,000 $; whereas, the minimum cost objective function value was 146,000 $ and the GWP value obtained at that cost was 1,250,000 kg of $CO_2$ equivalents. Thus, a 15% in cost reduction can be achieved when minimizing cost and 27% in GWP reduction can be attained when minimizing GWP, with respect to the maximum value of cost when reducing GWP, and the maximum value of GWP when reducing cost, respectively. To investigate the tradeoffs between minimizing costs and minimizing GWP, the *Simplified Yearly LCA Optimization Model* was used to find the optimal solutions between the two extreme points by minimizing GWP at fixed cost values. Figure 5-72 shows the Pareto optimal frontier for GWP and cost objective functions obtained by using the *Simplified Yearly LCA Optimization Model*.

When minimizing cost, most of the power demand was supplied by the average electric grid throughout the year except when the thermal demand was high, as in the months of January, February, March, November and October, where part of the power demand was supplied by the ICE cogeneration systems. Consequently, the gas boiler provided most of the heating demand throughout the year except in the heating months, and cooling was provided by the electric chillers throughout the year and partially by the absorption chiller in the heating months. When minimizing GWP, on the other hand, most of the power requirements were supplied by the ICE cogeneration system and to a lesser extent by the MT cogeneration system while the average electric grid was used minimally. Consequently, the heating demand was met by the cogenerated heat from the cogeneration systems except in the heating months where the gas boiler supplied part of the heating requirements; the cooling demand was met by the absorption chillers throughout the year except when the cooling demand was high, as in the months of May through September where part of the cooling requirement was supplied by the electric chillers.

As shown in Figure 5-72, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 160,000 $) indicates a gradual decrease in GWP values as the cost values increased and the second region (points that laid beyond the cost of 160,000 $) indicates the plateau of the GWP and cost values where the decrease in GWP values to the minimum GWP value was very low. As the cost increased from 146,000 \$ to 155,000 \$, a 6% increase in cost, the GWP decreased from 1,250,000 kg of $CO_2$ equivalents to 948,000 kg of $CO_2$ equivalents, a 24% decrease in GWP; the power supply shifted gradually from the average electric grid as the main power supply to ICE cogeneration system with a decrease in the average electric grid use. The GWP values continued to decrease gradually as more of the power supply shifted from the average electric grid to the ICE and MT cogeneration systems up to the point when the cost was 160,000 \$; after that point the GWP values plateau and the GWP value was further decreased by only 3% to the minimum GWP while the cost increased by an additional 12%, where most of the power was supplied by the ICE cogeneration system.

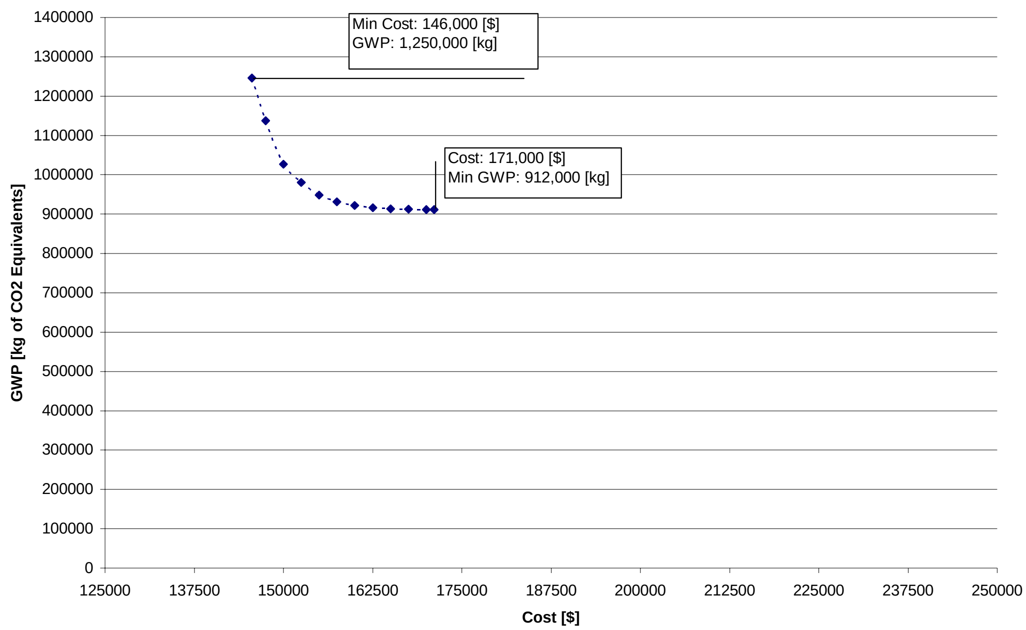



**Figure 5-72: Pareto optimal frontier for GWP and cost (Yearly Model).**

When inspecting the results of each day in the 12 months using the *Hourly LCA Optimization Model*, the results showed that the highest reduction in GWP (up to 38% in July) was obtained in the cooling months with only a 17% increase in cost relative to the minimum cost. Whereas, in the heating months, such as in January, the total reduction in GWP is only 10% relative to the GWP that was obtained when minimizing cost. The increase in cost to achieve the minimal GWP is approximately equal to the increase in the cooling months. However, in the cooling months, the values of GWP corresponding to the minimum cost were higher than those obtained in the heating months. For example, in a typical day in July, at the minimum cost of 418 $, GWP was 4149 kg of $CO_2$ equivalents whereas in January, at the minimum cost of 513 $, GWP was 3464 kg of $CO_2$ equivalents, which is 16% lower than in July. Figure 5-73 shows the Pareto optimal frontier for GWP and cost objective functions obtained by using the *Hourly LCA Optimization Model* in the 12 average days in the 12 months.

The preceding occurred mainly because when minimizing cost in the heating months, part of the power and thermal demand was supplied by the ICE cogeneration system, due to its high thermal efficiency ratio, in addition to the average electric grid. In the cooling months the average electric grid was used to meet all of the power demand because the thermal demand was low and the cost of obtaining power from the average electric grid was lower than the ICE cogeneration system. When minimizing GWP, the higher decrease in GWP in the cooling months was due to the shift from supplying power from the average electric grid and heat from the gas boiler to using the ICE and MT cogeneration systems to supply the power and thermal demand. The lower decrease in GWP in the heating months, on the other hand, was because the ICE was already used when minimizing cost. The ICE (in addition to the MT cogeneration system) completely replaced the average electric grid when minimizing GWP, resulting in lower GWP.

Therefore, the highest potential for reducing GWP (up to 38% in July) occurred in the cooling months by shifting fulfilling the power demand from the average electric grid to the ICE and MT cogeneration systems, and also shifting the heating demand from the gas boiler to the cogenerated heat from the cogeneration systems. Consequently, the use of electric chillers to meet the cooling demand would be replaced by absorption chillers. That was achieved while increasing cost by only 17% to 20%.

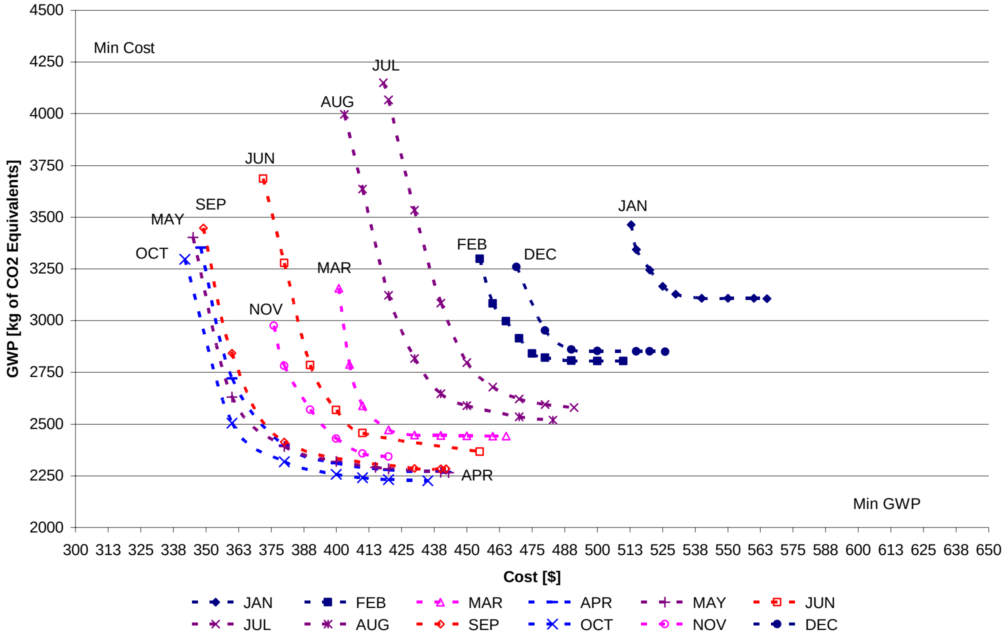



**Figure 5-73: Pareto optimal frontier for GWP and cost (Hourly Model).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing $CO_2$ and cost objective functions, the minimum $CO_2$ objective function value was 819,000 kg and the cost required to achieve that value was 168,000 $; whereas, the minimum cost objective function value was 146,000 $ and the $CO_2$ value obtained at that cost was 116,000 kg. Thus, a 13% cost reduction can be achieved when minimizing cost with respect to the maximum value of cost when minimizing $CO_2$. A 29% $CO_2$ reduction can be attained when minimizing $CO_2$, relative to the maximum value of $CO_2$ when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing $CO_2$, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing $CO_2$ at fixed cost values. Figure 5-74 shows the Pareto optimal frontier for $CO_2$ and cost objective functions obtained by using the *Simplified LCA Optimization Model*.

Since the results from minimizing $CO_2$ resembled the results obtained from minimizing GWP, the reasoning behind the reduction in emissions follows the same pattern. As shown in Figure 5-74, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 160,000 $) indicates a gradual decrease in $CO_2$ values as the cost values increased, and the second region (points that laid beyond the cost value of 160,000 $) indicates the plateau of the $CO_2$ and cost values where the decrease in $CO_2$ values to the minimum $CO_2$ value was very low. $CO_2$ was reduced by 26% with only a 6% increase in cost with respect to the minimum cost with the increased use of ICE to meet the energy demand throughout the year rather than just partially during the heating months. At the plateau region, an additional 3% of $CO_2$ was reduced to the minimum $CO_2$ with an additional 9% increase in cost. As in the case of GWP and cost minimization, the power shifted from being supplied by primarily the average electric grid to mainly the ICE cogeneration system and partially the MT cogeneration system. Similarly, heat was mainly supplied by the cogeneration systems except in the heating months where the gas boiler supplemented the heating supply when required. The absorption chiller was used to meet the cooling demand while the electric chiller was used to meet partially the cooling demand when required in the cooling months.

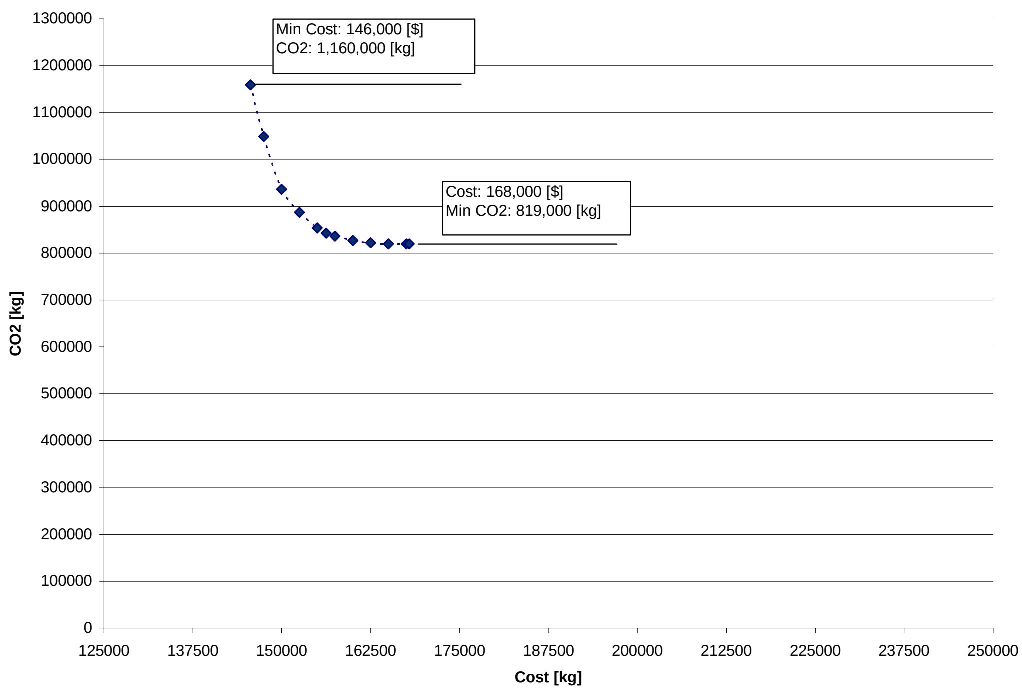



**Figure 5-74: Pareto optimal frontier for $CO_2$ and cost (Yearly Model).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing TOPP and cost objective functions, the minimum TOPP objective function value was 395 kg of TOPP equivalents and the cost required to achieve that value was 239,000 $; whereas, the minimum cost objective function value was 146,000 $ and the TOPP value obtained at that cost was 5419 kg of TOPP equivalents. Thus, a 39% reduction in cost can be achieved when minimizing cost with respect to the maximum value of cost when minimizing TOPP. A 92% reduction in TOPP can be attained when minimizing TOPP with respect to the maximum value of TOPP when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing TOPP, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing TOPP at fixed cost values. Figure 5-75 shows the Pareto optimal frontier for TOPP and cost objective functions obtained by using the *Simplified LCA Optimization Model*.

When minimizing TOPP, most of the power requirements were supplied by the SOFC and MT cogeneration system. Consequently, the heating demand was met by the cogenerated heat from the cogeneration systems. The cooling demand was met by the absorption chillers throughout the year except when the cooling demand was high where part of the cooling requirement was supplied by the electric chillers.

As shown in Figure 5-75, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 212500 $) indicates a gradual decrease in TOPP values as the cost values increased, and the second region (points that laid beyond the cost value of 212500 $) indicates the plateau of the TOPP and cost values where the decrease in TOPP values (with increase in cost) to the minimum TOPP value was very low. As the cost increased from 146,000 $ to 175,000 $, a 20% increase in cost, the TOPP decreased by 57% from 5419 kg of TOPP equivalents to 2333 kg of TOPP equivalents; the power supply shifted gradually from the average electric grid as the main power supply to partial supply by the MT cogeneration system while the average electric grid remained to contribute a high proportion of the power supply. An increase of MT cogeneration system use occurred when the cost was 187,500 $, which increased the cost by only an additional 7% but the TOPP was reduced further by an additional 17%. As the SOFC was introduced when the cost was 200,000 $ (37% higher than the minimum cost), the total reduction in TOPP obtained relative to that obtained at minimum cost was 82% at the value of 975 kg of TOPP equivalents. After that point the TOPP value continued to decrease until it stabilized at 420 kg of TOPP equivalents where the cost was 212,500 $, a 46% reduction in cost from the minimum cost. While there was no significant reduction in TOPP only an additional 1% increase, the minimum value of TOPP of 395 kg of TOPP equivalents was obtained at 238,703 $, an additional 18% increase in cost. Thus, with the introduction of MT cogeneration system, up to 57% reduction in TOPP can be achieved with only a 20% increase in cost with respect to the minimum cost. Up to 93% of TOPP could be reduced when the SOFC was used in addition to MT cogeneration system with 53% increase in cost relative to the minimum cost.

The results of each day in the 12 months using the *Hourly LCA Optimization Model*, showed that a 89% (in heating months) to 94% (in cooling months) reduction in TOPP was attained in all days but the highest cost to achieve that reduction was during the heating months. For example, a cost increase of 83% occurred in January versus only 49% in July with respect to the minimum cost in those months. This was because the higher amount of power that was required to be produced to meet the thermal demand with cogenerated heat from the SOFC and MT when minimizing TOPP in the heating months compared to the cooling months. This translated in higher cost of energy production in the cooling versus the heating months. Figure 5-76 shows the Pareto optimal frontier for TOPP and cost objective functions obtained by using the *Hourly LCA Optimization Model* in the 12 average days in the 12 months. Therefore, generally TOPP reduction was high throughout the year (89%-94% reduction compared to the highest value obtained at minimum cost). However, the highest potential for reducing TOPP with lowest cost could be achieved in the cooling months.

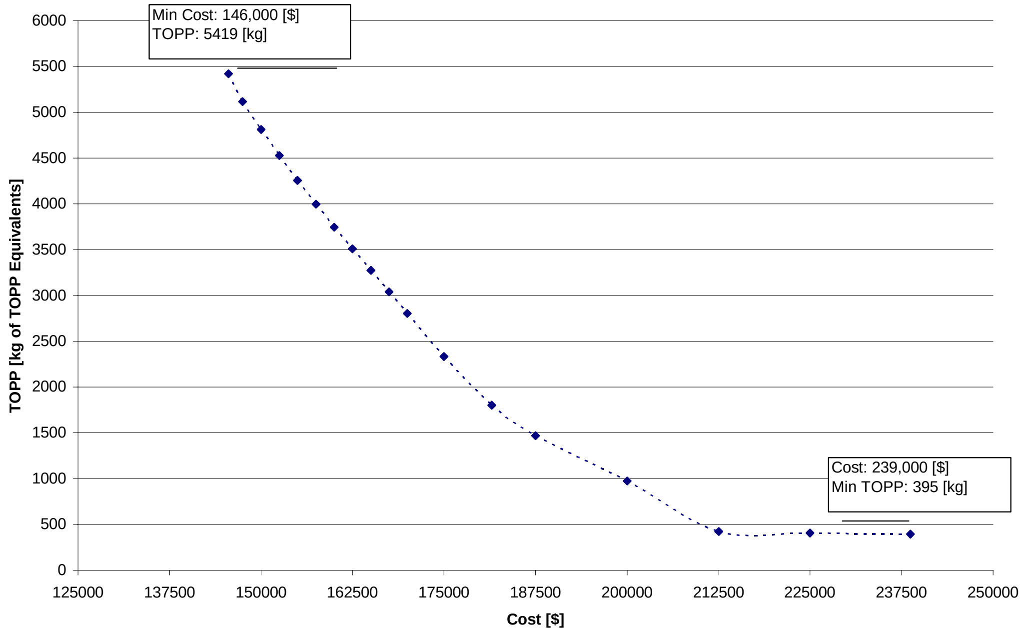



**Figure 5-75: Pareto optimal frontier for TOPP and cost (Yearly Model).**

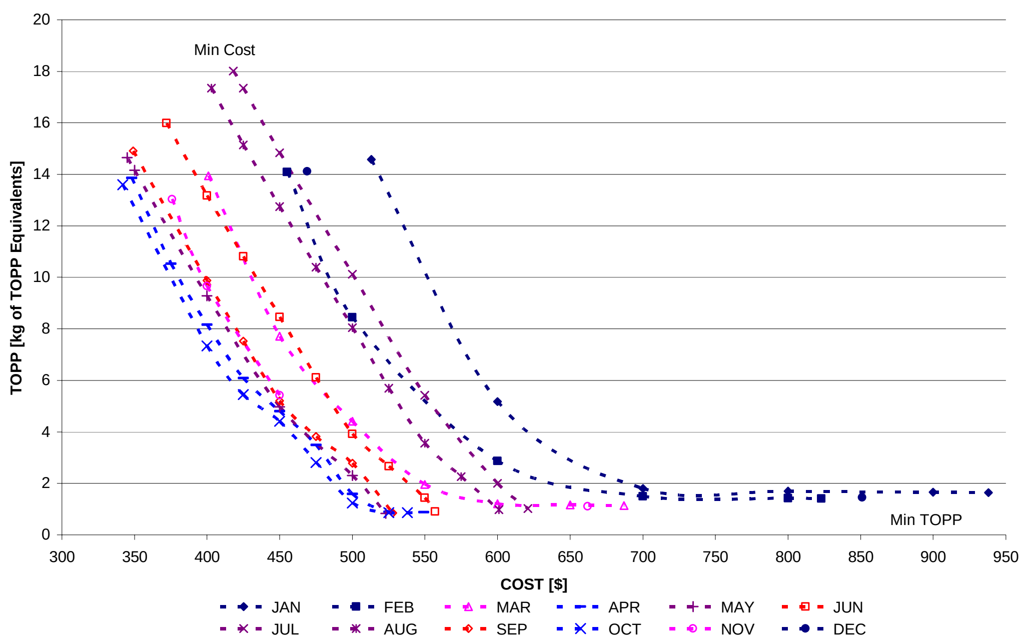



**Figure 5-76: Pareto optimal frontier for TOPP and cost (Hourly Model).**

When analyzing the results obtained from the *Simplified LCA Optimization Model* for minimizing AP and cost objective functions, the minimum AP objective function value was 225 kg of $SO_2$ equivalents and the cost required to achieve that value was 230,000 $; whereas, the minimum cost objective function value was 146,000 $ and the AP value obtained at that cost was 3786 kg of $SO_2$ equivalents. A 37% in cost reduction was achieved when minimizing cost with respect to the maximum value of cost when minimizing AP. A 94% reduction in AP was attained when minimizing AP with respect to the maximum value of AP when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing AP, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing AP at fixed cost values. Figure 5-77 shows the Pareto optimal frontier for AP and cost objective functions obtained by using the *Simplified LCA Optimization Model*.

When minimizing AP, most of the power requirements were supplied by the SOFC and MT cogeneration system. Consequently, the heating demand was met by the cogenerated heat from the cogeneration systems. The cooling demand was met by the absorption chillers throughout the year except when the cooling demand was high, when part of the cooling requirement was supplied by the electric chillers.

As shown in Figure 5-77, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 212500 $) indicates a gradual decrease (almost in a linear fashion) in AP values as the cost values increased, and the second region (points that laid beyond the cost value of 212500 $) indicates the plateau of the AP and cost values where the decrease in AP values (with increase in cost) to the minimum AP value was very low. As the cost increased from 146,000 $ to 152,500 $, a 5% increase in cost, the AP decreased by 24% from 3786 kg of $SO_2$ equivalents to 2893 kg of $SO_2$ equivalents; the power supply shifted gradually from the average electric grid as the main power supply to partial supply by the ICE cogeneration system (and minimally by the MT cogeneration system). The heating demand, on the other hand, was supplied mainly in the cooling months by the cogenerated heat from the cogeneration system, and the cooling supply shifted from being supplied by the electric chiller (as was the case when minimizing cost) to the absorption chiller. An additional 19% reduction in AP was achieved with an additional 5% increase in cost (160,000 $), since the MT cogeneration system use increased, providing a higher proportion of the power supply in addition to the ICE cogeneration system and the average electric grid.

The AP continued to decrease dramatically, as the MT cogeneration system supplied more of the power and the ICE cogeneration system and the average electric grid contribution to power supply decreased. At the cost of 187,500 $, an additional 19% increase in cost, the value of AP was 1002 kg of $SO_2$ equivalents, a total of 73% reduction in AP relative to the AP value at minimum cost. The ICE cogeneration system was no longer in use and the power supply was provided by the MT cogeneration system and partially by the average electric grid. AP continued to decrease and at the value of 231 kg of $SO_2$ equivalents, a total of 94% in AP reduction relative to the value obtained at minimum cost, the SOFC was in use and supplied part of the energy requirement in addition to the MT cogeneration system, causing an increase in cost to 212,500 $, a 46% increase in cost relative to the value obtained at minimum cost. The AP value then stabilized and the minimum value of AP was obtained at a 58% increase in total cost, relative to the minimum cost.

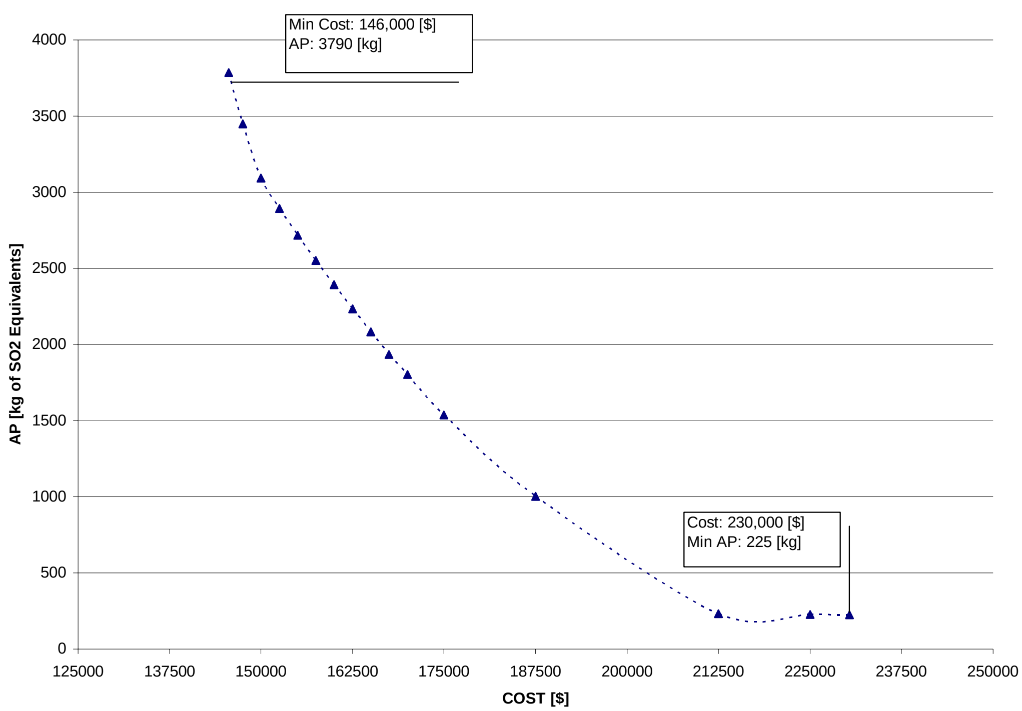



**Figure 5-77: Pareto optimal frontier for AP and cost (Yearly Model).**

When analyzing the results obtained from the *Simplified LCA Optimization Model* for minimizing $NO_x$ and cost objective functions, the minimum $NO_x$ objective function value was 228 kg and the cost required to achieve that value was 231,000 $. The minimum cost objective function value was 146,000 $ and the $NO_x$ value obtained at that cost was 3975 kg. Thus, a 37% cost reduction can be achieved when minimizing cost with respect to the maximum value of cost when minimizing $NO_x$. A 93% reduction in $NO_x$ can be attained when minimizing $NO_x$ relative to the maximum value of $NO_x$ when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing $NO_x$, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing $NO_x$ at fixed cost values. Figure 5-78 shows the Pareto optimal frontier for $NO_x$ and cost objective functions obtained by using the *Simplified LCA Optimization Model*.

The results generally resembled those obtained from the Pareto optimal solutions for minimum AP and cost. As shown in Figure 5-78, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 212,500 $) indicates a gradual decrease (almost in a linear fashion) in $NO_x$ values as the cost values increased, and the second region (points that laid beyond the cost value of 212,500 $) indicates the plateau of the $NO_x$ and cost values where the decrease in $NO_x$ values (with increase in cost) to the minimum $NO_x$ value was very low. As the cost increased from 146,000 $ to 152,500 $, a 5% increase in cost, the $NO_x$ decreased by 17% from 3975 kg to 3285 kg. The power supply shifted gradually from the average electric grid as the main power supply to partial supply by the ICE cogeneration system and minimally by the MT cogeneration system. The average electric grid remained to contribute a high proportion of the power supply. For an additional 1% increase in cost, at the cost of 155,000 $, $NO_x$ was reduced to 23% of the value obtained at minimum cost. At this point, the ICE cogeneration system was not in use and the power was supplied mainly by the average electric grid and partially by the MT cogeneration system, which supplied more of the power and heating demand in the heating months. $NO_x$ continued to decrease and at a 29% increase in cost relative to the minimum cost (187,500 $), $NO_x$ was 1043 kg, representing a 74% reduction compared to the $NO_x$ value obtained at minimum cost. The MT cogeneration system supplied most of the energy requirement and the average electric grid and the gas boiler supplemented the energy supply. At the cost of 200,000 $, the SOFC was in use to supply part of the energy requirement, causing a total of 83% in $NO_x$ reduction relative to the value obtained at minimum cost. $NO_x$ continued to be reduced as the SOFC supplied more of the energy requirement along with the MT cogeneration system. The power supply from the average electric grid was continually reduced until the minimum $NO_x$ was obtained for a 59% increase in cost relative to the minimum cost. The average electric grid was no longer in use, and the MT and SOFC supplied all of the energy requirements of the building.

Generally, the similarity between the results derived for the Pareto optimal frontier for TOPP, AP and $NO_x$ with respect to cost was because the $NO_x$ value was the major contributor in the TOPP and AP indicators, hence when minimizing the three objective functions similar results were obtained.

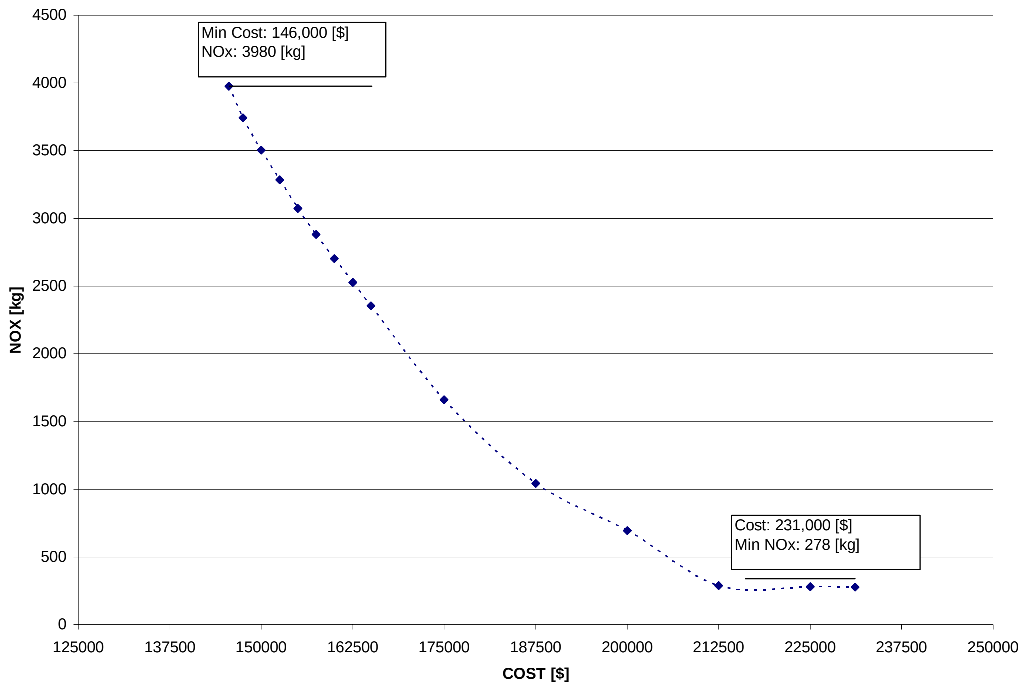



**Figure 5-78: Pareto optimal frontier for $NO_x$ and cost (Yearly Model).**

When analyzing the results obtained from the *Simplified LCA Optimization Model* for minimizing $SO_2$ and cost objective functions, the minimum $SO_2$ objective function value was 18 kg and the cost required to achieve that value was 174,000 $; whereas, the minimum cost objective function value was 146,000 $ and the $SO_2$ value obtained at that cost was 950 kg. Thus, 16% in cost reduction can be achieved when minimizing cost and 98% in $SO_2$ reduction can be attained when minimizing $SO_2$, with respect to the maximum value of cost when minimizing $SO_2$, and the maximum value of $SO_2$ when minimizing cost, respectively. To investigate the tradeoffs between minimizing costs and minimizing $SO_2$, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing $SO_2$ at fixed cost values. Figure 5-79 shows the Pareto optimal frontier for $SO_2$ and cost objective functions obtained by using the *Simplified LCA Optimization Model*.

As shown in Figure 5-79, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 155,000 $) indicates a sharp decrease in $SO_2$ values with minimal increase in cost, and the second region (points that laid beyond the cost value of 155,000 $) indicates a gradual decrease in the $SO_2$ to the minimum value of with a gradual increase in cost. $SO_2$ was reduced by 84% with only 10% increase in cost with respect to the minimum cost by increasing the use of ICE to meet the energy demand throughout the year. When minimizing cost, ICE is used to partially supply energy during the heating months. An additional 14% of $SO_2$ was reduced to achieve the minimum $SO_2$, which incurred an additional 10% increase in cost. Like in the case of GWP and cost minimization problems, the power shifted from being supplied by primarily the average electric grid to mainly the ICE cogeneration system and partially the MT cogeneration system. Similarly, heat was mainly supplied by the cogeneration systems except in the heating months where the gas boiler supplemented the heating supply when required. The absorption chiller was used to meet the cooling demand while the electric chiller was used to meet part of the cooling demand in the cooling months.

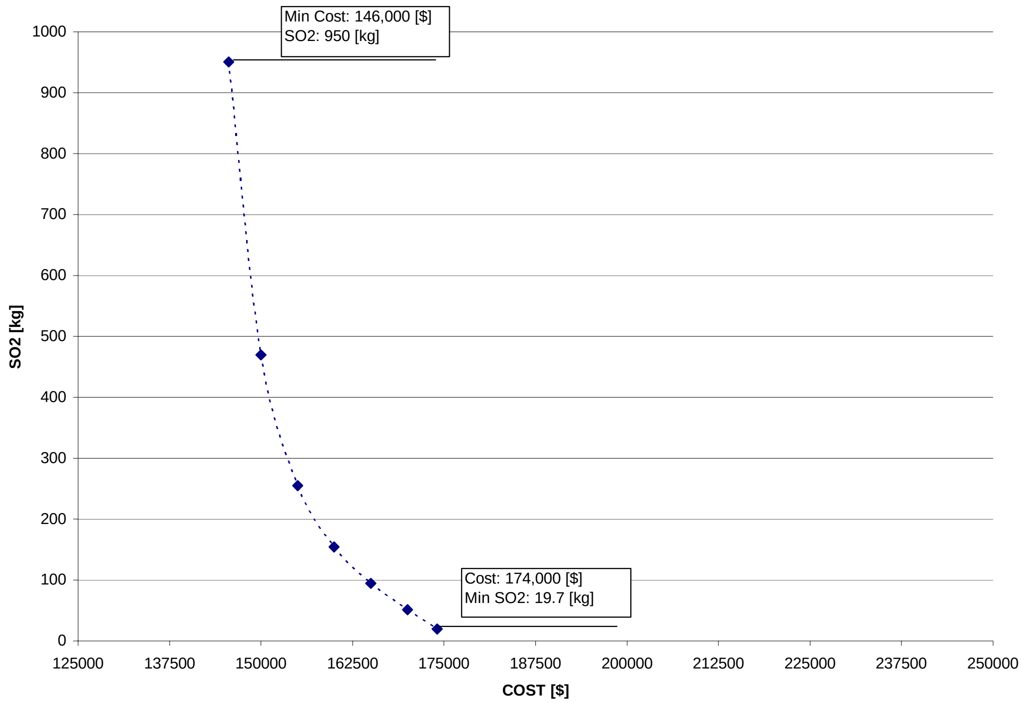



**Figure 5-79: Pareto optimal frontier for $SO_2$ and cost (Yearly Model).**

When analyzing the results obtained from the *Simplified LCA Optimization Model* for minimizing PE consumption and cost objective functions, the minimum PE consumption objective function value was 4,460,000 kWh and the cost required to achieve that value was 191,000 $. The minimum cost objective function value was 146,000 $ and the PE value obtained at that cost was 5,220,000 kWh. Thus, a 24% cost reduction can be achieved when minimizing cost with respect to the maximum value of cost when minimizing PE consumption. A 14% reduction in PE consumption can be attained when minimizing PE consumption relative to the maximum value of PE when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing PE consumption, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing PE at fixed cost values. Figure 5-80 shows the Pareto optimal frontier for the PE consumption and cost objective functions obtained by using the *Simplified LCA Optimization Model*.

As shown in Figure 5-80, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 160,000 $) indicates a gradual decrease in PE values as the cost values increased, and the second region (points that laid beyond the cost value of 160,000 $) indicates the plateau of the PE and cost values where the decrease in PE values to the minimum PE value was minimal. As the cost increased from 146,000 $ to 150,000 $, a 3% increase in cost, the PE value decreased by 10% from 5,220,000 kWh to 4,680,000 kWh; the energy supply from the ICE cogeneration system increased, especially in the heating months, while the average electric grid continued to supply most of the power demand and the MT cogeneration system was used minimally to supply part of the energy requirement. An additional 4% decrease in PE was obtained as the ICE and MT cogeneration energy supply increased and the power supply from the average electric grid decreased, with an additional 10% increase in cost. This trend continued until at the minimum PE value of 4,460,000 kWh, obtained at a total of 31% increase in cost relative to the minimum cost, where the SOFC supplied part of the energy demand in addition to the ICE cogeneration system and to a lesser extent the MT cogeneration system while the average electric grid use to supply power was minimal.

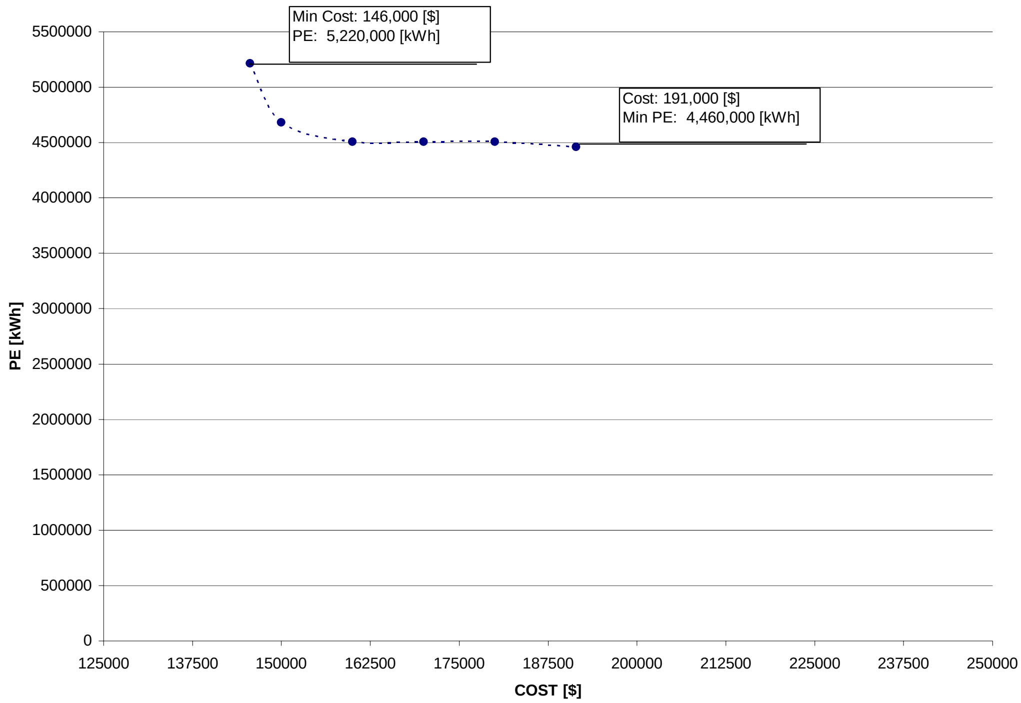



**Figure 5-80: Pareto optimal frontier for PE and cost (Yearly Model).**

The results obtained from the Pareto optimal solutions for the environmental indicators and cost indicated that a sharp decrease in GWP, $CO_2$, $SO_2$ and PE indicator values relative to the values obtained at minimum cost were achievable with a relatively low increment in cost, due to the shift of energy use from the average electric grid as the main power source when minimizing cost to cogeneration systems when minimizing the environmental indicators. Figure 5-81 shows the Pareto optimal frontier for the normalized environmental and cost objective functions obtained by using the *Simplified LCA Optimization Model*. A 29% decrease in $CO_2$ value relative to the $CO_2$ value obtained at minimum cost was achievable with only a 15% increase in cost, relative to the minimum cost value. Likewise, a 27% decrease in GWP value was attainable with only a 18% increase in cost; a 14% decrease in PE value with a 31% increase in cost if the SOFC was in use and only a 24% increase in cost if it was not in use. An approximately, a 98% decrease in $SO_2$ was achievable with only a 20% increase in cost, reflecting the difference between the high $SO_2$ emission factors of the average electric grid relative to the cogeneration systems.

On the other hand, the decrease in TOPP, AP and $NO_x$ indicator values relative to the values obtained at minimum cost was gradual with high increment in cost values, reflecting the shift in use from the average electric grid to ICE and MT cogeneration systems and finally, the SOFC cogeneration system, resulting in high cost. An approximately a 94% decrease in AP, a 93% decrease in TOPP and a 93% decrease in $NO_x$ indicator values (relative to the values obtained at minimum cost) were attainable with a 58%, 64% and 59% increase in cost relative to the minimum cost values, respectively.

The difference in the trends between the first group of indicators: GWP, PE, $CO_2$ and $SO_2$, and the second group of indicators: TOPP, AP and $NO_x$ was mainly because: first, the cost difference between the average electric grid (which was the main source for power supply when minimizing cost) and the cost of using cogeneration systems, when minimizing the first group of indicators, was low leading to a considerable decrease in the values of the indicators with a minimal increase in cost; and second, because the difference between the indicator factors associated with the average electric grid and the cogeneration systems was significant leading to considerable decrease in the values of the indicators from those obtained at minimum cost. However, with the second group of indicators (TOPP, AP and $NO_x$) the decrease in indicator values was gradual with higher increment in cost values mainly because the difference in cost between the average electric and the SOFC and MT cogeneration systems was very high.

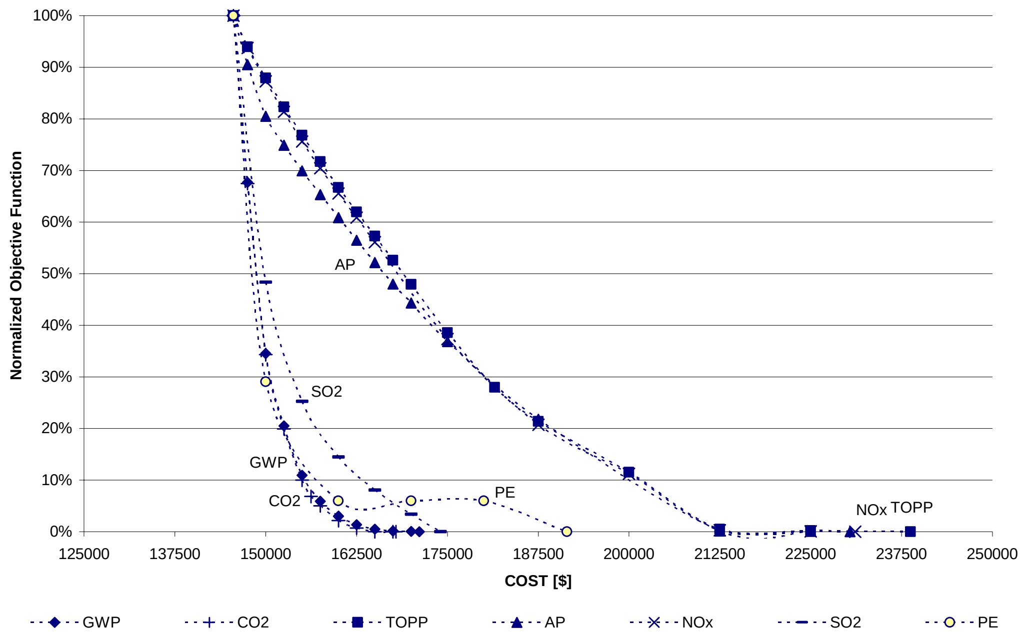



**Figure 5-81: Pareto optimal frontier for normalized environmental indicators and cost (Yearly Model).**

### 5.3.2 Problems Set II: Electric Utility Option (2): NGCC Power Plant

#### 5.3.2.1 Minimizing GWP & $CO_2$

When using the *Hourly LCA Optimization Model* to minimize the objective functions in the 12 average days in the months of January through December, for the GWP and $CO_2$ objective functions, the results of the optimization model showed that the NGCC power plant and ICE cogeneration system were used primarily to meet the power demand of the building. Figures 5-82, 5-83 and 5-84 show the percent power, heating and cooling supply of the energy systems in the 12 average days in the months of January through December for minimizing GWP.

The heat was mostly supplied by the cogeneration systems when minimizing both GWP and $CO_2$ except in the heating months when the thermal demand was higher and the gas boiler was used to supplement the heating supply. The cooling demand was mostly supplied with electric chillers and partially by the absorption chiller when minimizing GWP. However, when ICE use was higher when minimizing $CO_2$, the cogenerated heat from the ICE system supplied the necessary thermal energy to drive the absorption chillers and therefore, the absorption chillers were used to supply most of the cooling demand except when the cooling demand was higher and the electric chillers supplied part of the cooling requirements.

Unlike the results obtained from the *Hourly LCA Optimization Model* for minimizing GWP and $CO_2$ in problems set I (with the average electric grid as the power utility option) where the ICE and MT cogeneration systems provided most of the power requirements of the building with minimal use of the average electric grid, the solution of the current problem showed that the NGCC provided most of the power requirement for GWP minimization problem. This was because of the lower GWP and $CO_2$ emission factors of the NGCC power plant compared to the average electric grid which make it competitive with the cogeneration systems. Although the GWP and $CO_2$ emission factors for the NGCC power plant was lower than those of the ICE and MT cogeneration systems, the optimum found from the optimization results was to use the ICE and MT cogeneration systems to meet part of the electrical demand because the cogenerated heat was used to meet most of the thermal demand. The proportion of cogeneration systems use increased in the heating months with the increase in the thermal demand. The MT cogeneration system was not used in the cooling months when the heating demand was low as in the months of May through September but was used partially when the heating demand was higher in the remainder of the months.

When minimizing $CO_2$, on the other hand, the proportion of electric supply from the NGCC power plant decreased compared to the GWP minimization results. The ICE cogeneration system provided more than 50% of the power demand, especially in the heating months when it provided about 70% of the power demand. The shift in power supply when compared to the GWP minimization results is due to the lower $CO_2$ emission factor values of the ICE compared to its GWP emission factor values. While the $CO_2$ and GWP emission factors of both the NGCC power plant and MT cogeneration system are approximately equal, the relatively higher $CH_4$ emission factor of the ICE, compared to the NGCC and MT systems, lead to the increase the GWP emission factor of the ICE.

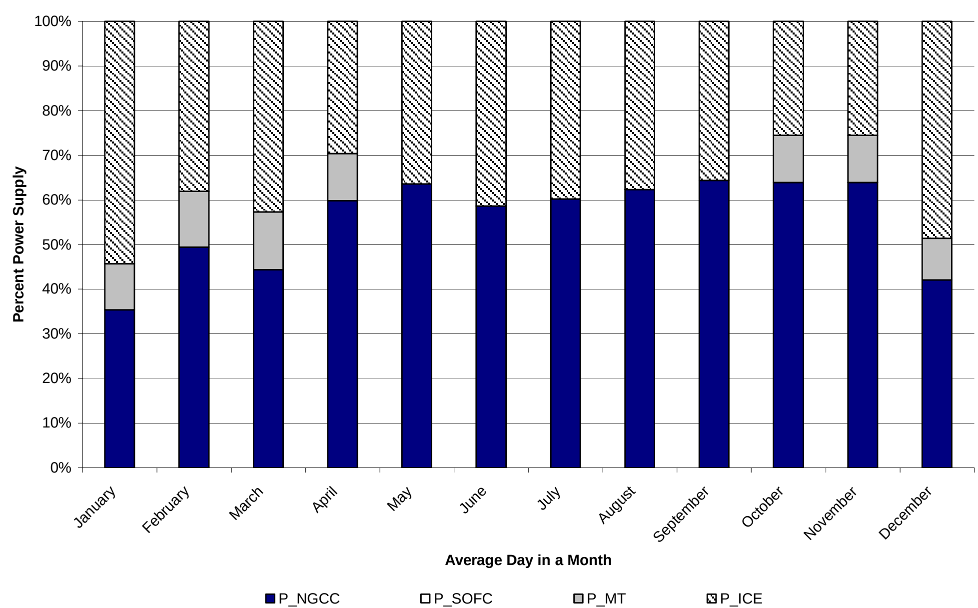



**Figure 5-82: Percent power supply from energy systems: Hourly Model for min GWP (NGCC).**

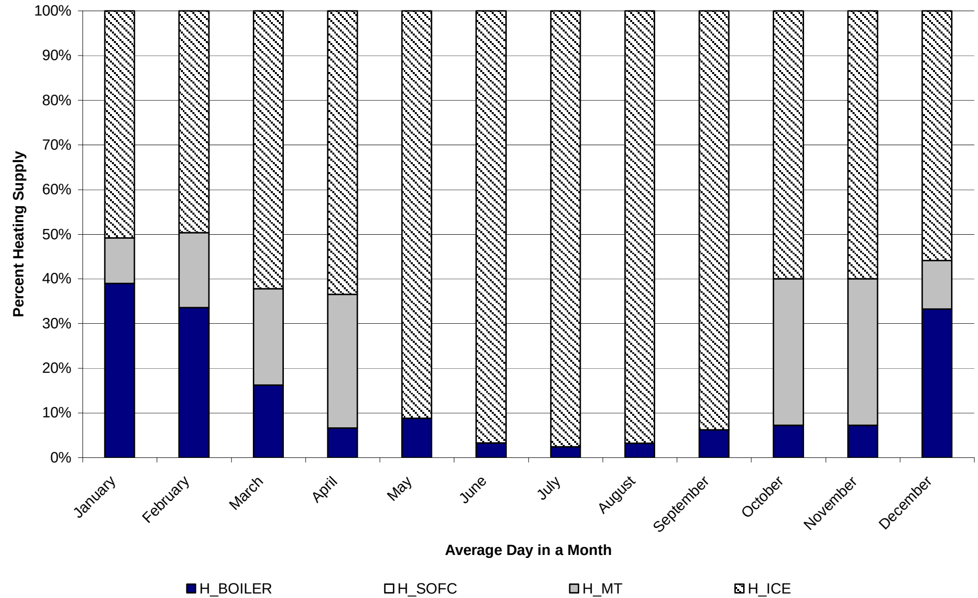



**Figure 5-83: Percent heating supply from energy systems: Hourly Model for min GWP (NGCC).**

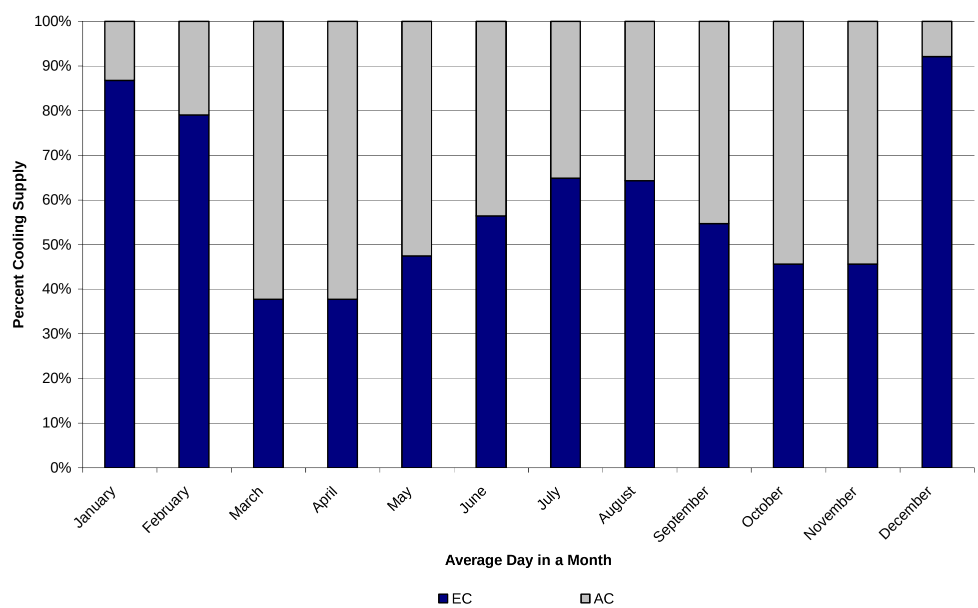



**Figure 5-84: Percent cooling supply from energy systems: Hourly Model for min GWP (NGCC).**

When using the *Simplified Yearly LCA Optimization Model* to minimize GWP and $CO_2$, the results obtained were similar to those obtained from the *Hourly LCA Optimization Model*. Figures 5-85 and 5-86 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing GWP, respectively. Figures 5-87 and 5-89 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing GWP, respectively. Figures 5-90 and 5-91 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing GWP, respectively. The graphs indicate the similarity in operational trends of the building.

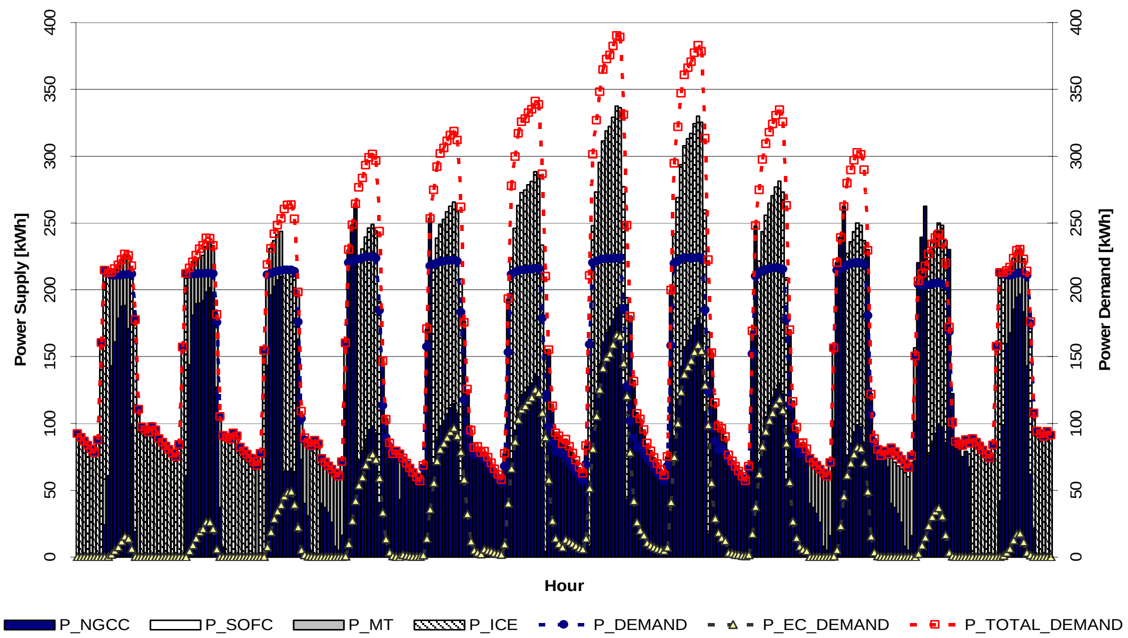



**Figure 5-85: Power supply: solution from Hourly model (NGCC) for min GWP.**

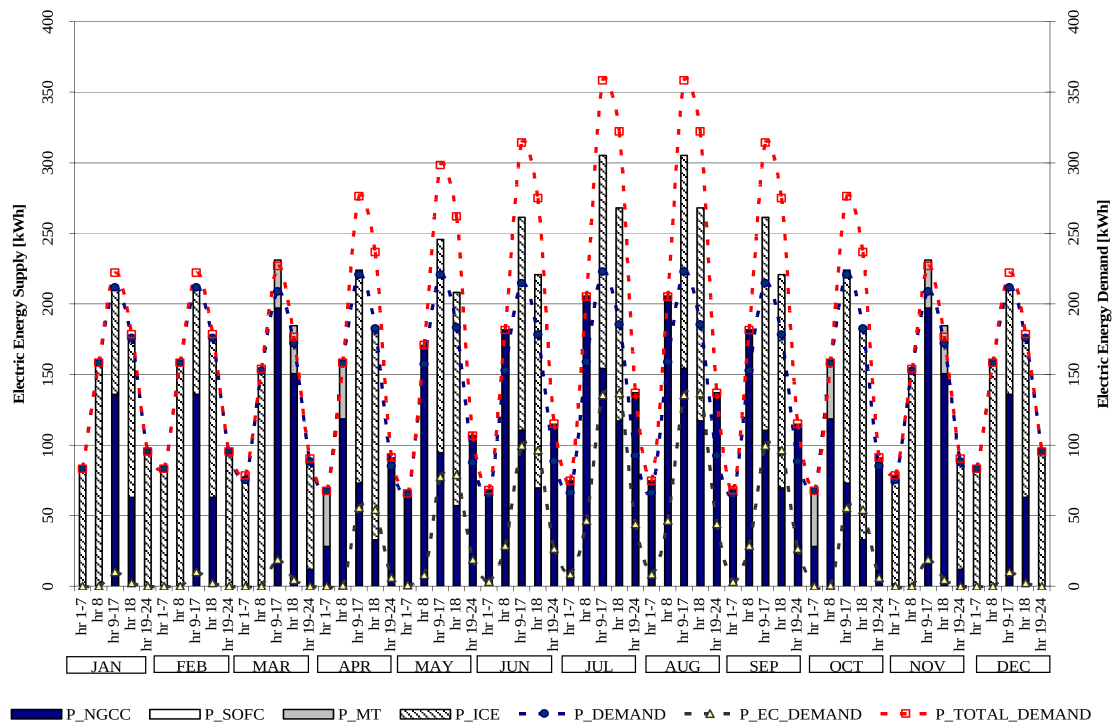



**Figure 5-86: Power supply: solution from Yearly model (NGCC) for min GWP**

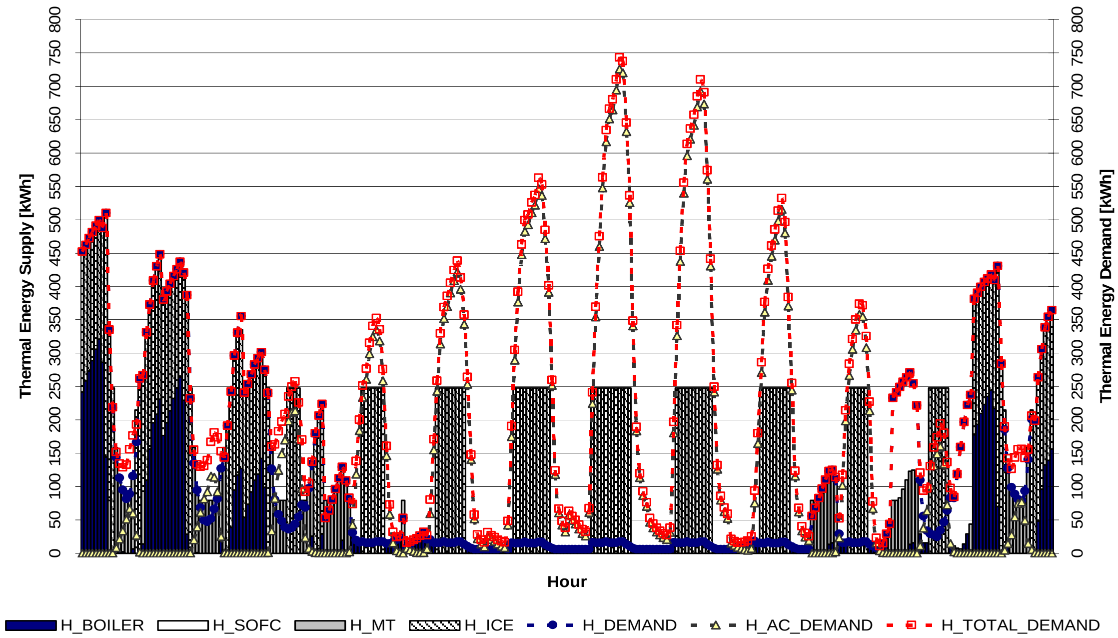



**Figure 5-87: Heating supply: solution from Hourly model (NGCC) for min GWP.**

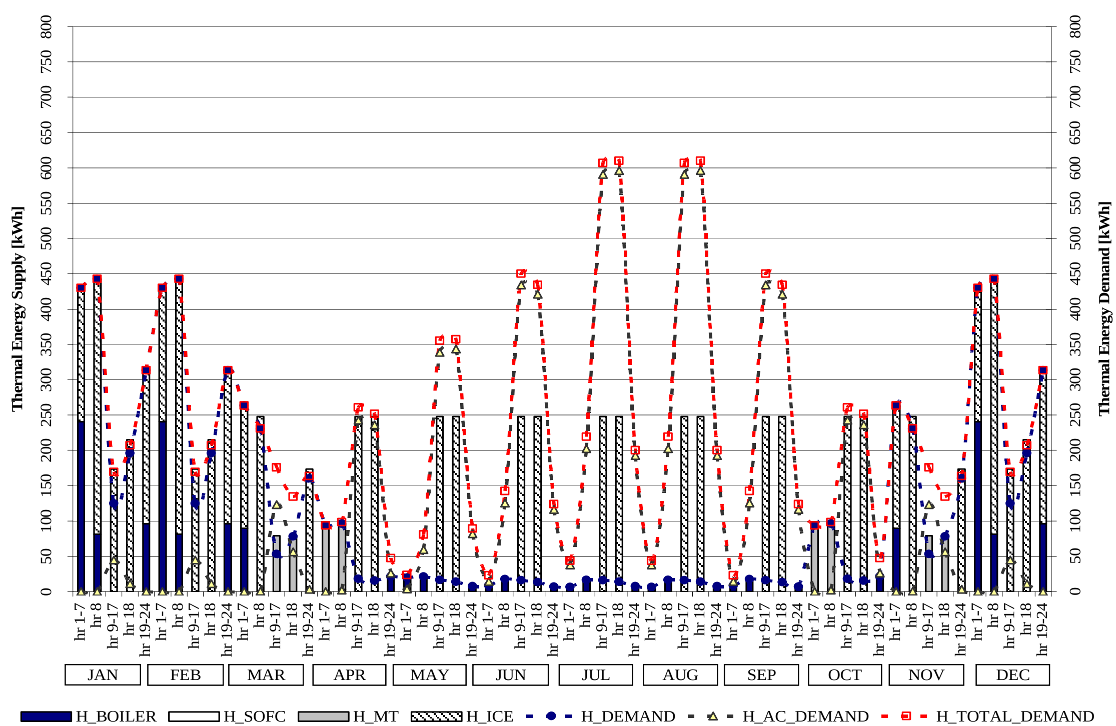



**Figure 5-88: Heating supply: solution from Yearly model (NGCC) for min GWP.**

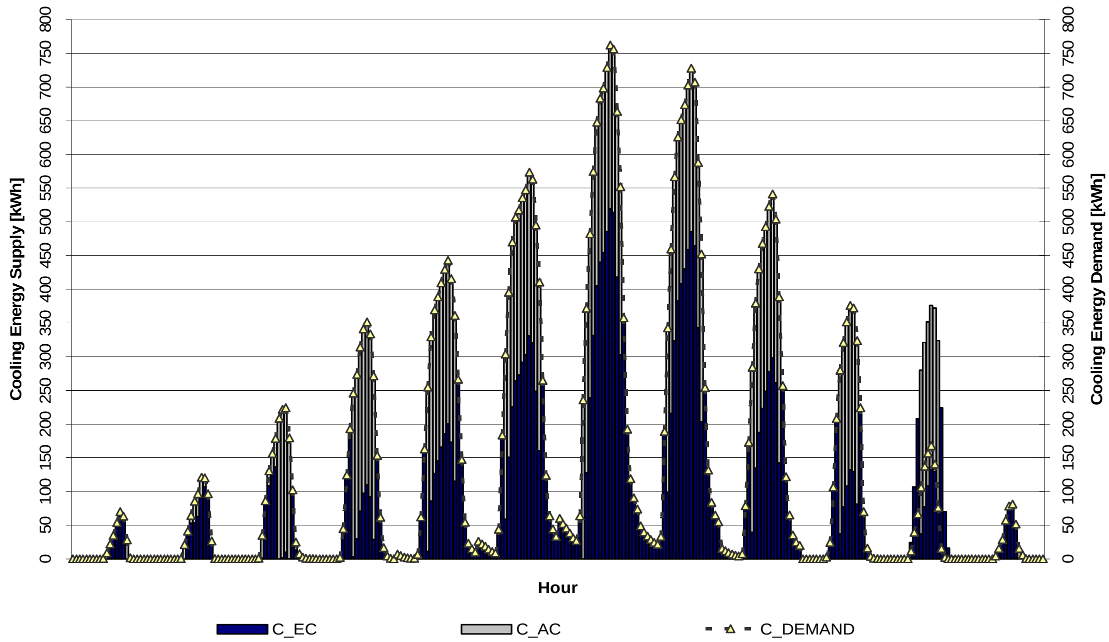



**Figure 5-89: Cooling supply: solution from Hourly model (NGCC) for min GWP**

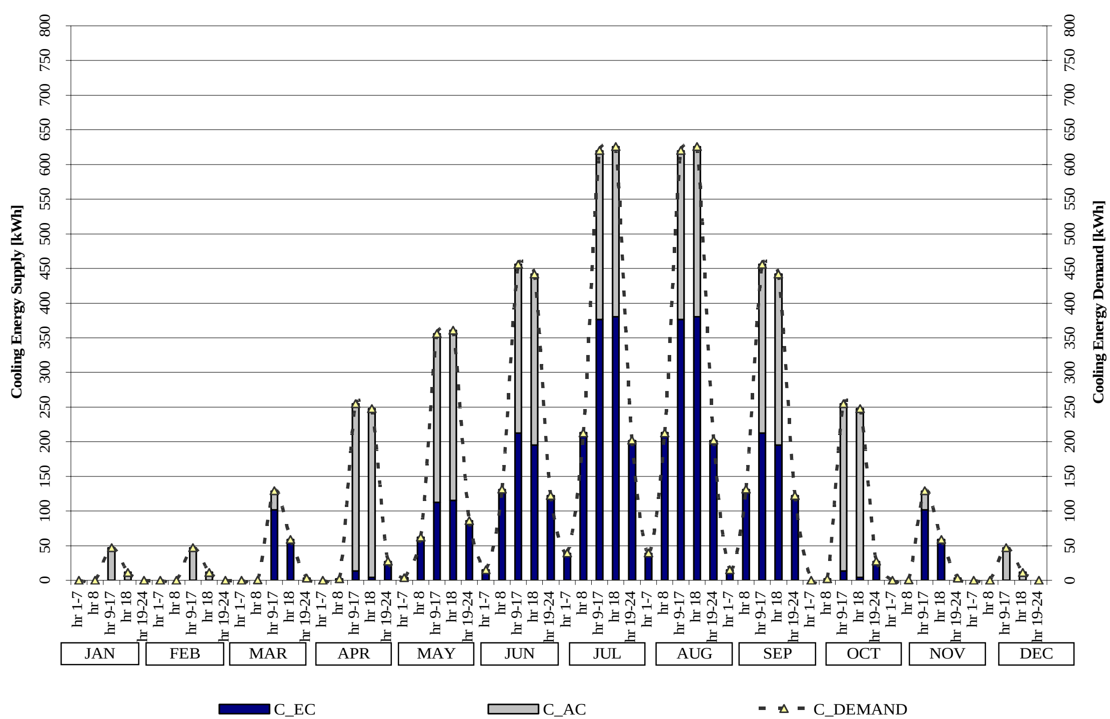



**Figure 5-90: Cooling supply: solution from Yearly model (NGCC) for min GWP.**

When using the *Hourly LCA Optimization Model* to minimize GWP and $CO_2$, the objective functions had the highest values in the heating months and lowest values in the months of April, May, September and October whereas in the cooling months, the values of the objective function increased and reached a peak in the month of July. Generally, the values of all the indicators followed the same trend as that exhibited by the objective function and reflected the emission factor characteristics of the energy systems used at those points. This can be seen in Figures 5-91 and 5-92, which shows the normalized values of the GWP and $CO_2$ objective functions, respectively, and the respective values of the other indicators in the 12 average days in the 12 months. Tables 5-16 and 5-17 show the GWP and $CO_2$ objective functions values and the corresponding indicators values in the 12 average days in the months.

The results obtained from the *Simplified Yearly LCA Optimization Model*, generated the total values of the objective function and the corresponding values of the other indicators. Figure 5-93 shows the values of GWP expressed in *kg of $CO_2$ equivalents* corresponding to each objective function and Figure 5-94 shows the $CO_2$ values in *kg* corresponding to each objective function obtained from the *Simplified Yearly LCA Optimization Model* results. When minimizing GWP, PE, $CO_2$, $SO_2$ and cost the values of GWP corresponding to the objective functions obtained were approximately equal, but the values of GWP increased by about 68% when minimizing TOPP, AP and $NO_x$. Similarly when minimizing GWP, PE, $CO_2$, $SO_2$ and cost the values of $CO_2$ obtained corresponding to the objective functions were approximately equal, but the values of $CO_2$ increased by about 80% when minimizing TOPP, AP and $NO_x$. This mainly because the SOFC, which was used to meet part of the electrical and thermal demand when minimizing TOPP, AP and $NO_x$, has high GWP and $CO_2$ emission factors compared to the other systems.

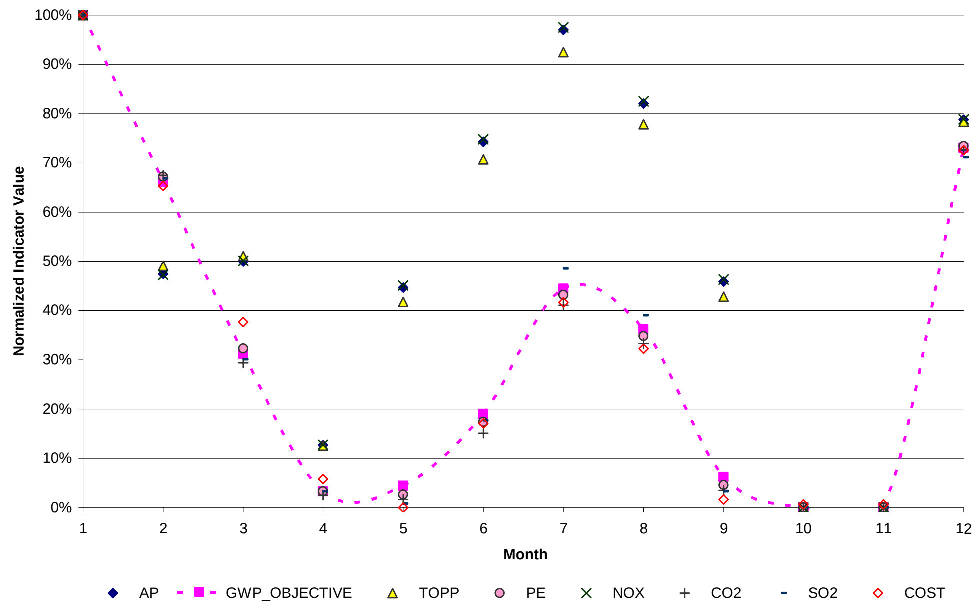



**Figure 5-91: Normalized indicator values corresponding to GWP objective function (Hourly Model-NGCC).**

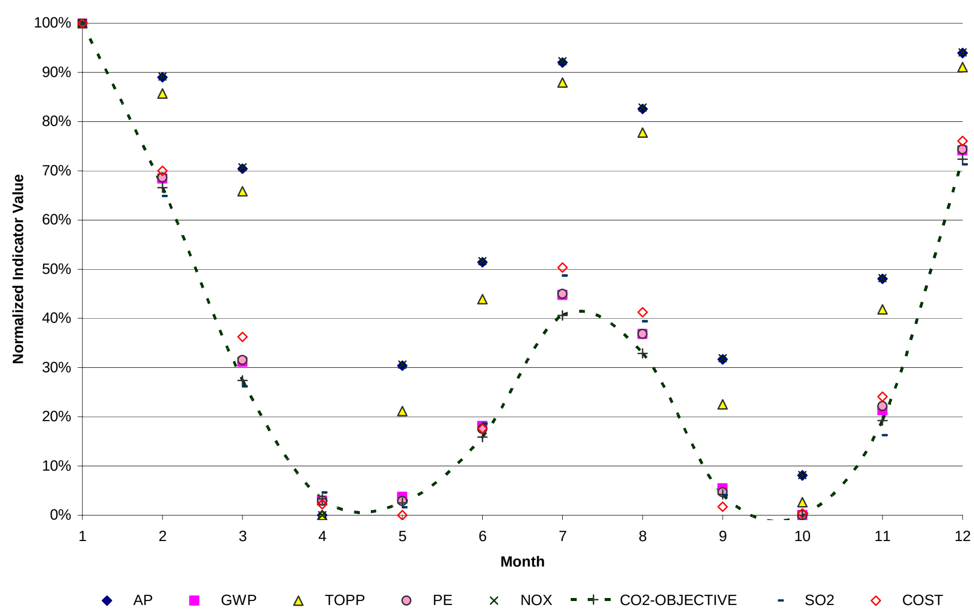


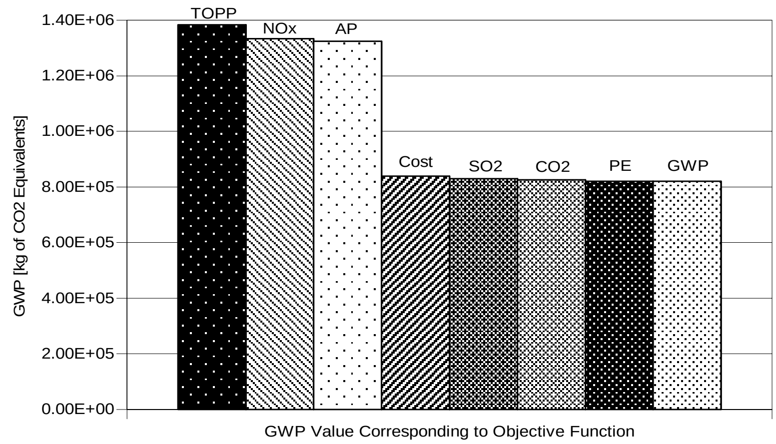

**Figure 5-92: Normalized indicator values corresponding to $CO_2$ objective function (Hourly Model-NGCC).**

**Table 5-16: Indicator values corresponding to GWP objective function (Hourly Model-NGCC).**

| | AP | GWP Objective | TOPP | PE | $NO_x$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 5.05E+00 | 2.93E+03 | 1.00E+01 | 1.49E+04 | 7.16E+00 | 2.73E+03 | 6.29E-02 | 5.08E+02 |
| February | 3.95E+00 | 2.58E+03 | 7.88E+00 | 1.32E+04 | 5.58E+00 | 2.42E+03 | 5.65E-02 | 4.47E+02 |
| March | 4.00E+00 | 2.23E+03 | 7.96E+00 | 1.14E+04 | 5.67E+00 | 2.07E+03 | 4.95E-02 | 3.98E+02 |
| April | 3.21E+00 | 1.94E+03 | 6.33E+00 | 9.94E+03 | 4.55E+00 | 1.82E+03 | 4.44E-02 | 3.41E+02 |
| May | 3.89E+00 | 1.95E+03 | 7.57E+00 | 9.90E+03 | 5.52E+00 | 1.81E+03 | 4.39E-02 | 3.31E+02 |
| June | 4.51E+00 | 2.10E+03 | 8.79E+00 | 1.07E+04 | 6.41E+00 | 1.93E+03 | 4.71E-02 | 3.61E+02 |
| July | 4.98E+00 | 2.36E+03 | 9.72E+00 | 1.20E+04 | 7.08E+00 | 2.18E+03 | 5.30E-02 | 4.05E+02 |
| August | 4.67E+00 | 2.28E+03 | 9.10E+00 | 1.16E+04 | 6.63E+00 | 2.10E+03 | 5.12E-02 | 3.88E+02 |
| September | 3.91E+00 | 1.97E+03 | 7.61E+00 | 1.00E+04 | 5.56E+00 | 1.83E+03 | 4.44E-02 | 3.34E+02 |
| October | 2.95E+00 | 1.91E+03 | 5.80E+00 | 9.77E+03 | 4.17E+00 | 1.79E+03 | 4.37E-02 | 3.32E+02 |
| November | 2.95E+00 | 1.91E+03 | 5.80E+00 | 9.77E+03 | 4.17E+00 | 1.79E+03 | 4.37E-02 | 3.32E+02 |
| December | 4.60E+00 | 2.65E+03 | 9.12E+00 | 1.35E+04 | 6.53E+00 | 2.47E+03 | 5.74E-02 | 4.59E+02 |
| Lowest Value | 2.95E+00 | 1.91E+03 | 5.80E+00 | 9.77E+03 | 4.17E+00 | 1.79E+03 | 4.37E-02 | 3.31E+02 |
| Highest Value | 5.05E+00 | 2.93E+03 | 1.00E+01 | 1.49E+04 | 7.16E+00 | 2.73E+03 | 6.29E-02 | 5.08E+02 |

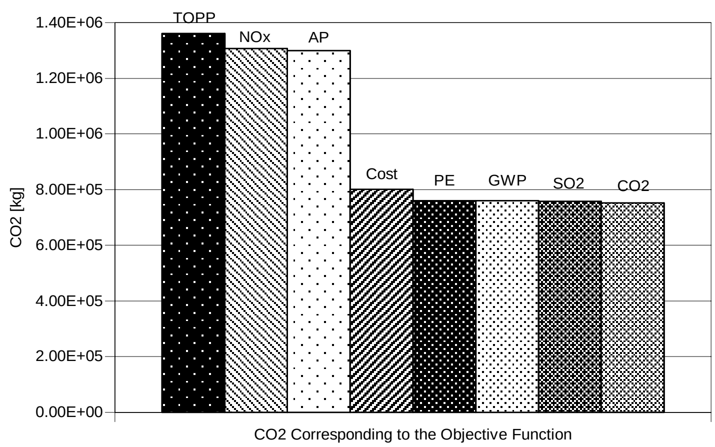
**Table 5-17: Indicator values corresponding to $CO_2$ objective function (Hourly Model-NGCC).**

| | AP | GWP | TOPP | PE | $NO_X$ | $CO_2$ Objective | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 6.79E+00 | 2.97E+03 | 1.35E+01 | 1.50E+04 | 9.67E+00 | 2.70E+03 | 6.23E-02 | 5.20E+02 |
| February | 6.45E+00 | 2.64E+03 | 1.27E+01 | 1.33E+04 | 9.18E+00 | 2.39E+03 | 5.57E-02 | 4.67E+02 |
| March | 5.86E+00 | 2.25E+03 | 1.16E+01 | 1.14E+04 | 8.35E+00 | 2.02E+03 | 4.83E-02 | 4.08E+02 |
| April | 3.64E+00 | 1.95E+03 | 7.79E+00 | 9.95E+03 | 5.17E+00 | 1.80E+03 | 4.42E-02 | 3.48E+02 |
| May | 4.60E+00 | 1.96E+03 | 9.01E+00 | 9.95E+03 | 6.54E+00 | 1.79E+03 | 4.36E-02 | 3.44E+02 |
| June | 5.26E+00 | 2.11E+03 | 1.03E+01 | 1.07E+04 | 7.49E+00 | 1.92E+03 | 4.69E-02 | 3.75E+02 |
| July | 6.54E+00 | 2.39E+03 | 1.28E+01 | 1.21E+04 | 9.32E+00 | 2.15E+03 | 5.26E-02 | 4.32E+02 |
| August | 6.24E+00 | 2.31E+03 | 1.23E+01 | 1.17E+04 | 8.89E+00 | 2.07E+03 | 5.08E-02 | 4.16E+02 |
| September | 4.64E+00 | 1.98E+03 | 9.08E+00 | 1.00E+04 | 6.60E+00 | 1.81E+03 | 4.41E-02 | 3.47E+02 |
| October | 3.90E+00 | 1.92E+03 | 7.94E+00 | 9.80E+03 | 5.53E+00 | 1.77E+03 | 4.33E-02 | 3.44E+02 |
| November | 5.15E+00 | 2.15E+03 | 1.02E+01 | 1.09E+04 | 7.34E+00 | 1.95E+03 | 4.64E-02 | 3.86E+02 |
| December | 6.60E+00 | 2.70E+03 | 1.30E+01 | 1.36E+04 | 9.40E+00 | 2.44E+03 | 5.69E-02 | 4.78E+02 |
| | | | | | | | | |
| Lowest Value | 3.64E+00 | 1.92E+03 | 7.79E+00 | 9.80E+03 | 5.17E+00 | 1.77E+03 | 4.33E-02 | 3.44E+02 |
| Highest Value | 6.79E+00 | 2.97E+03 | 1.35E+01 | 1.50E+04 | 9.67E+00 | 2.70E+03 | 6.23E-02 | 5.20E+02 |




| | GWP Value Corresponding to Objective Function |
|---|---|
| *TOPP Objective Function* | *1.38E+06* |
| *NOx Objective Function* | *1.33E+06* |
| *AP Objective Function* | *1.32E+06* |
| *Cost Objective Function* | *8.38E+05* |
| *SO2 Objective Function* | *8.30E+05* |
| *CO2 Objective Function* | *8.26E+05* |
| *PE Objective Function* | *8.21E+05* |
| *GWP Objective Function* | *8.21E+05* |

**Figure 5-93: Indicator values corresponding to GWP objective function (Yearly Model-NGCC).**




| | CO2 Corresponding to the Objective Function |
|---|---|
| *TOPP Objective Function* | *1.36E+06* |
| *NOx Objective Function* | *1.31E+06* |
| *AP Objective Function* | *1.30E+06* |
| *Cost Objective Function* | *8.01E+05* |
| *PE Objective Function* | *7.60E+05* |
| *GWP Objecitve Function* | *7.60E+05* |
| *SO2 Objective Function* | *7.57E+05* |
| *CO2 Objective Function* | *7.53E+05* |

**Figure 5-94: Indicator values corresponding to $CO_2$ objective function (Hourly Model-NGCC).**

#### 5.3.2.2 Minimizing AP, TOPP & $NO_X$

When using the *Hourly LCA Optimization Model* to minimize the AP, TOPP and $NO_x$ objective functions in the 12 average days in the months of January through December, the results of the optimization model showed that the SOFC and the MT cogeneration systems were used to meet the energy demand of the building. The results are similar to those obtained from the Problem set I (with the average electric grid option) for minimizing AP, TOPP and $NO_x$. For both problem sets, the AP, TOPP and $NO_x$ emission factors for the SOFC and MT are lower than the emission factors for the ICE, average electric grid and NGCC. Figures 5-95, 5-96 and 5-97 show the percent power supply, the percent heating supply, and the percent cooling supply, respectively, of the energy systems in each day of the months of January through December for minimizing AP. In the 12 average days, the proportion of the SOFC cogeneration system use to meet the electrical demand of the building increased when the thermal demand was low. Similarly, the proportion of the MT cogeneration system use increased when the thermal demand was high. The thermal demand of the building was supplied mainly by the MT cogeneration system and partially by the SOFC and minimally by the gas boiler when the heat supplied from the SOFC was not sufficient to meet the demand. The cooling demand was supplied mainly by absorption chiller, and in the months of March through October, as the cooling demand increased, the electric chiller supplied part of the cooling demand.

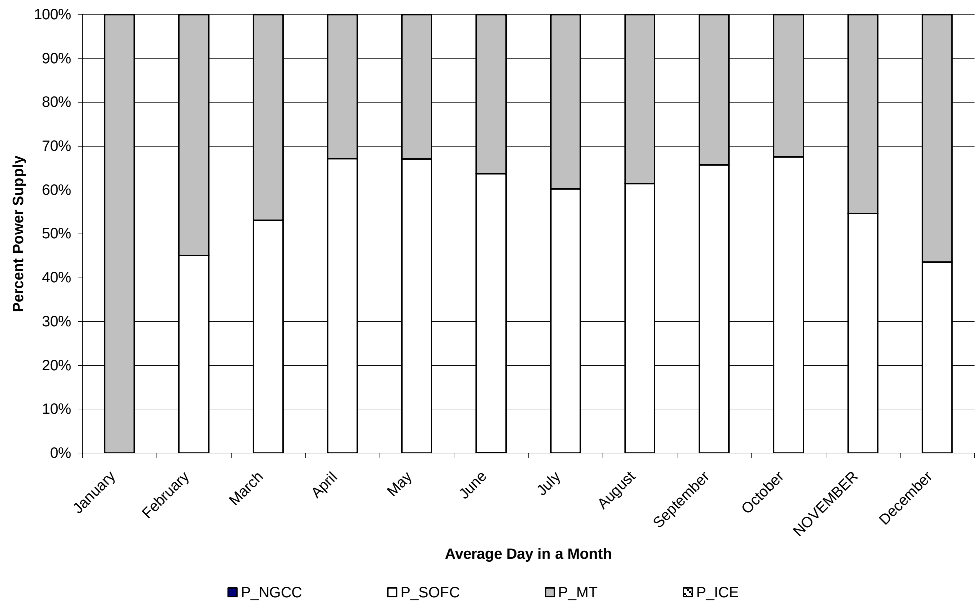



**Figure 5-95: Percent power supply from energy systems: Hourly Model for min AP (NGCC).**

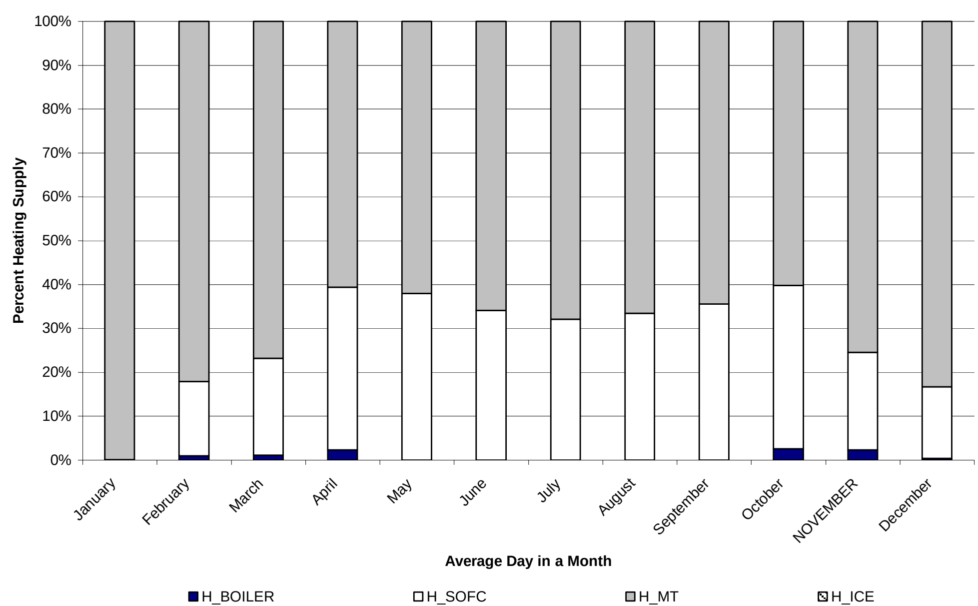



**Figure 5-96: Percent heating supply from energy systems: Hourly Model for min AP (NGCC).**

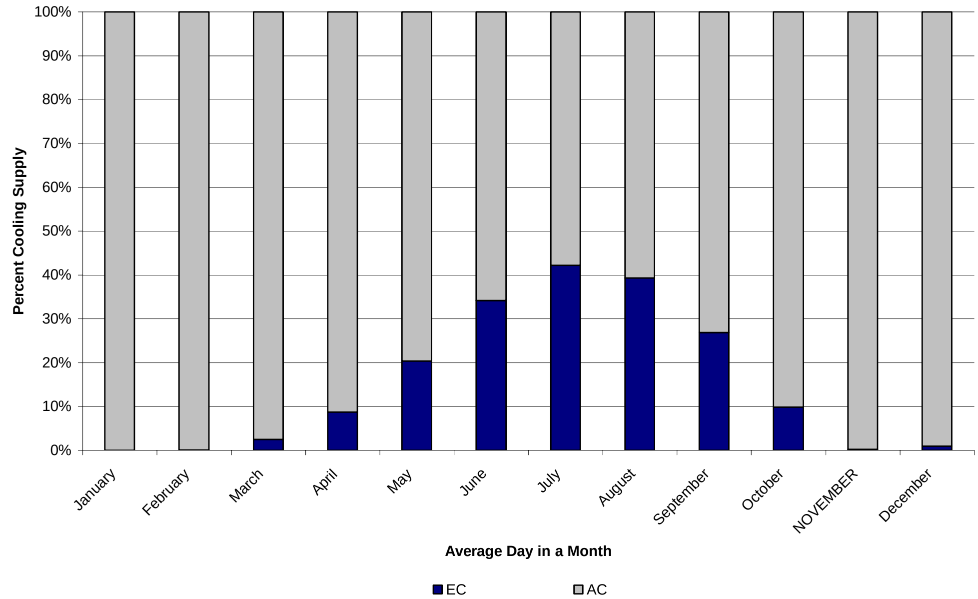



**Figure 5-97: Percent cooling supply from energy systems: Hourly Model for min AP (NGCC).**

When using the *Simplified Yearly LCA Optimization Model* to minimize the three objective functions in the year, the results resemble that obtained from the *Hourly LCA Optimization Model*. Figures 5-98 and 5-99 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing AP, respectively. Figures 5-100 and 5-101 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing AP, respectively. Figures 5-102 and 5-103 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing AP, respectively. The graphs indicate the similarity in operational trends of the building.

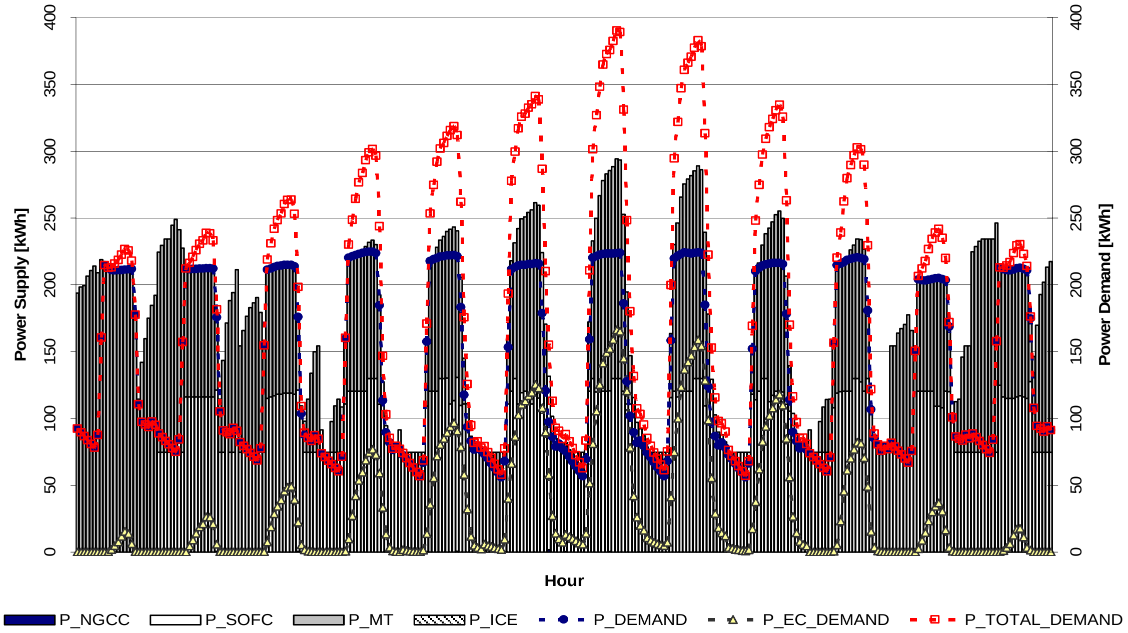



**Figure 5-98: Power supply: solution from Hourly model (NGCC) for min AP.**

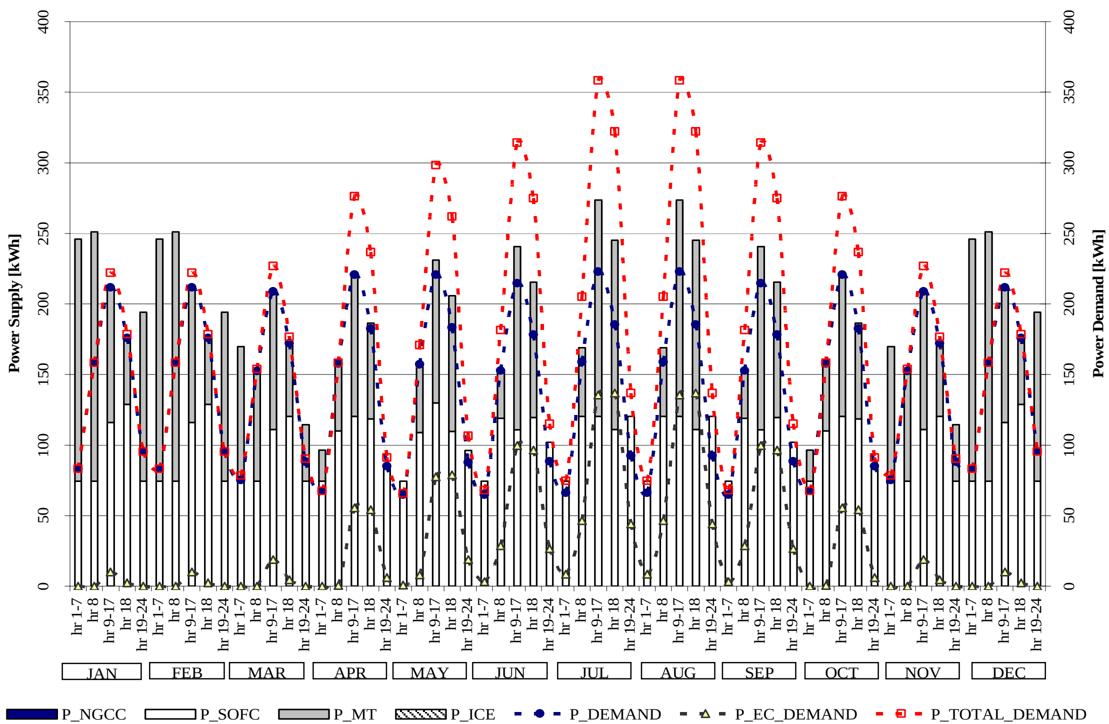



**Figure 5-99: Power supply: solution from Yearly model (NGCC) for min AP.**

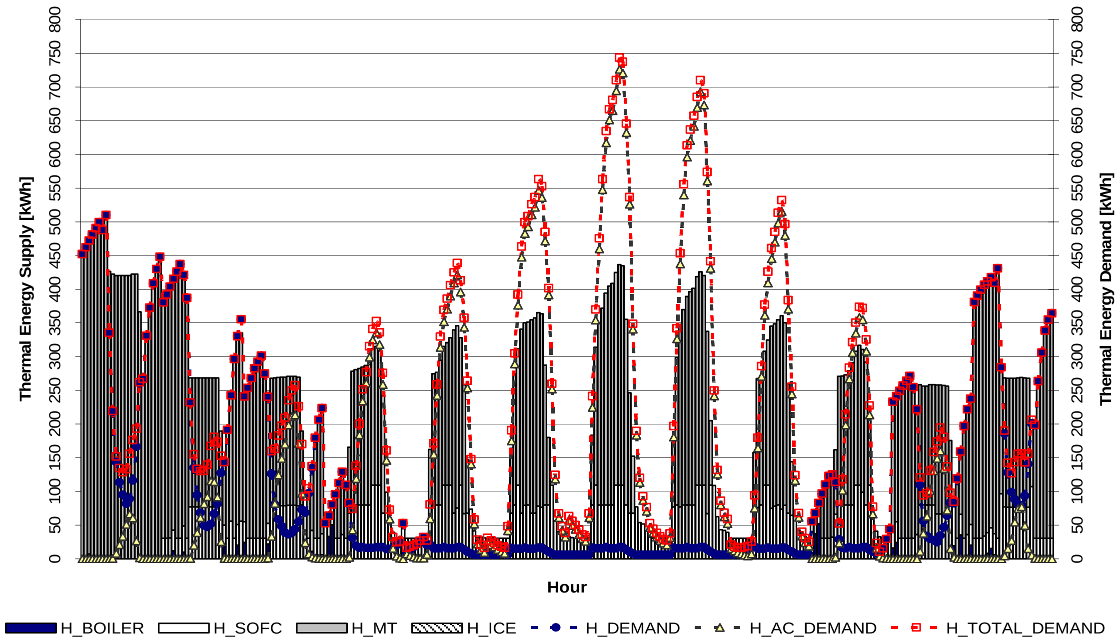



**Figure 5-100: Heating supply: solution from Hourly Model (NGCC) for min AP.**

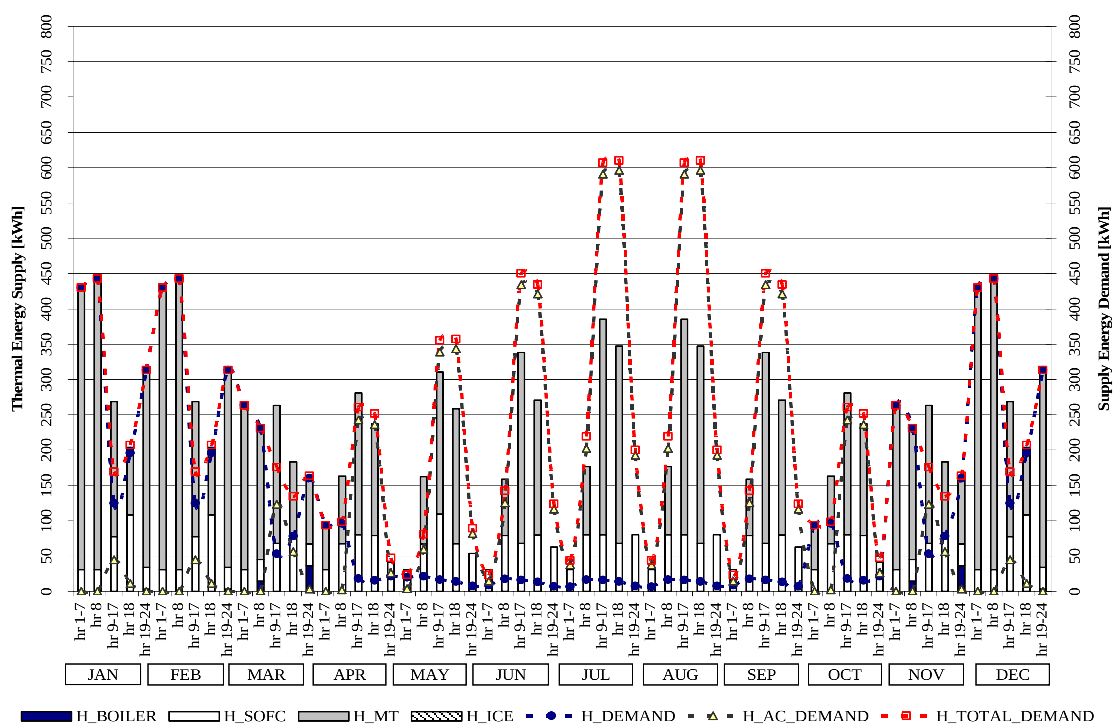



**Figure 5-101: Heating supply: solution from Yearly Model (NGCC) for min AP.**

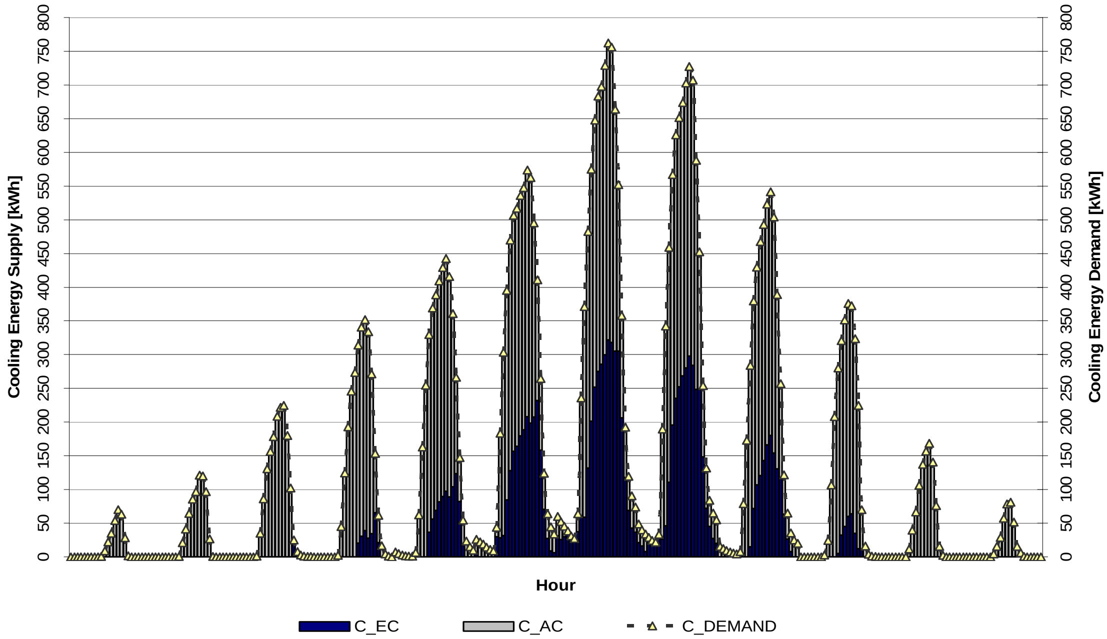



**Figure 5-102: Cooling supply: solution from Hourly Model (NGCC) for min AP.**

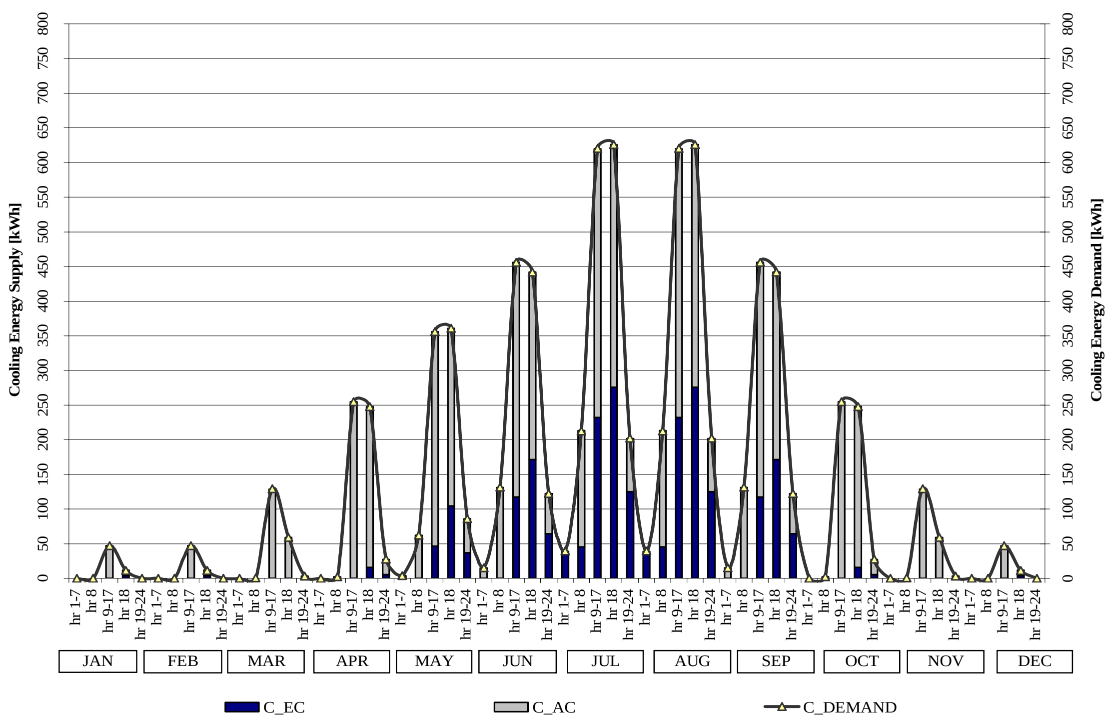



**Figure 5-103: Cooling supply: solution from Yearly Model (NGCC) for min AP.**

When minimizing AP, TOPP and $NO_x$, a similar trend was observed from the solution of the optimization problems. The trend in results was similar to that obtained from *Hourly Optimization Model* for problems in set I with the average electric grid option, when minimizing AP, TOPP and $NO_x$. Figures 5-104, 5-105 and 5-106 show the normalized objective function values of AP, TOPP and $NO_x$, respectively, in the 12 average days of January through December and the calculated values of the indicators corresponding to the minimum objective values. Generally, the lowest values of the three objective functions (AP, TOPP and $NO_x$) were obtained in the average day of April and May as well as September and October, and the highest values were obtained in the heating months of January, February and December. This trend reflects the higher use of the SOFC to meet part of the energy requirement (electrical as well as thermal) in May versus January. Generally, the values of the three objective functions (AP, TOPP and $NO_x$) increased relative to the values in April and May in the cooling months of June, July and August, with the increase in cooling demand. Tables 5-18, 5-19 and 5-20 show the values of the AP, TOPP and $NO_x$ objective functions, respectively, and the corresponding indicator values. Thus, if the highest value of the objective function is considered as 100%, then the low values of the objective functions (less than 10% of the maximum value) were attained in the transitional months of April, May, September, and October. The high values of the objective functions (more than 60% of the maximum value) were obtained in the heating months of January, February, and December. The objective functions values, which laid between 10% and 40% of the maximum value, occurred in the cooling months of June, July, and August as well as the transitional months of March and November.

The results obtained from the *Simplified Yearly LCA Optimization Model* generated the total values of the objective function and the corresponding values of the other indicators. Figures 5-107, 5-108 and 5-109 show the values of AP expressed in *kg of $SO_2$ equivalents*, TOPP expressed in *kg of TOPP equivalents*, and $NO_x$ expressed in *kg* corresponding to each objective function, respectively. When minimizing the AP, TOPP and $NO_x$, the values of AP obtained were approximately equal, but the values of the AP increased almost four times when minimizing cost, about seven times when minimizing GWP and PE and about nine times when minimizing $CO_2$ and $SO_2$. Similarly, the TOPP and $NO_x$ values obtained when minimizing AP, TOPP and $NO_x$ was much lower than the values of TOPP and $NO_x$ obtained when minimizing PE, GWP, $CO_2$, $SO_2$ and Cost. These trends reflect the characteristics of the energy systems used when minimizing each of the objective functions. The values of AP, TOPP and $NO_x$ increased with the increase in ICE cogeneration system use because ICE has higher AP, TOPP and $NO_x$ emissions compared to the other systems.

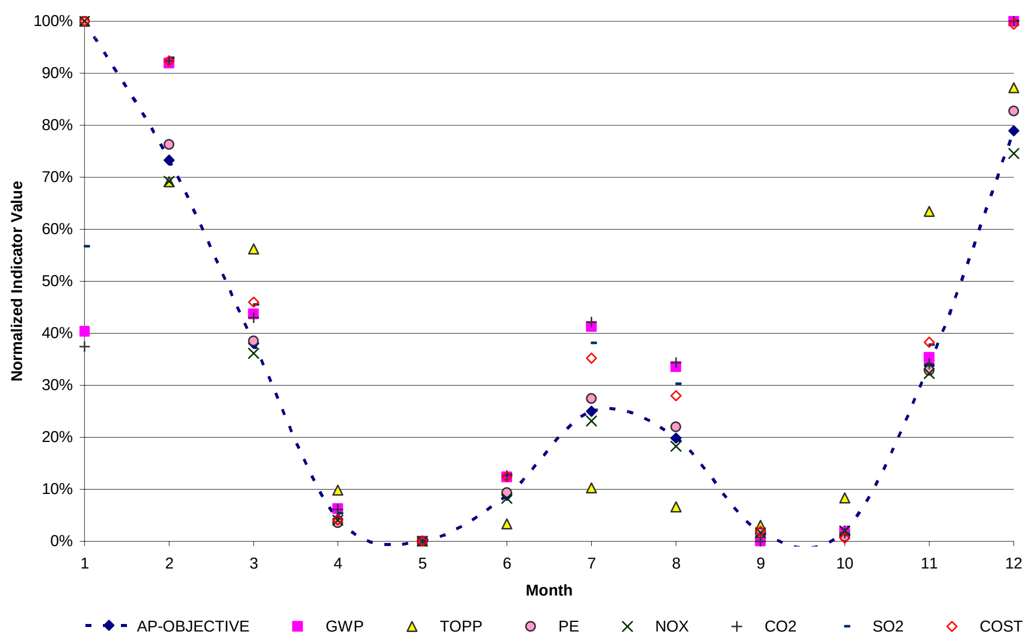



**Figure 5-104: Normalized indicator values corresponding to AP objective function (Hourly Model-NGCC).**

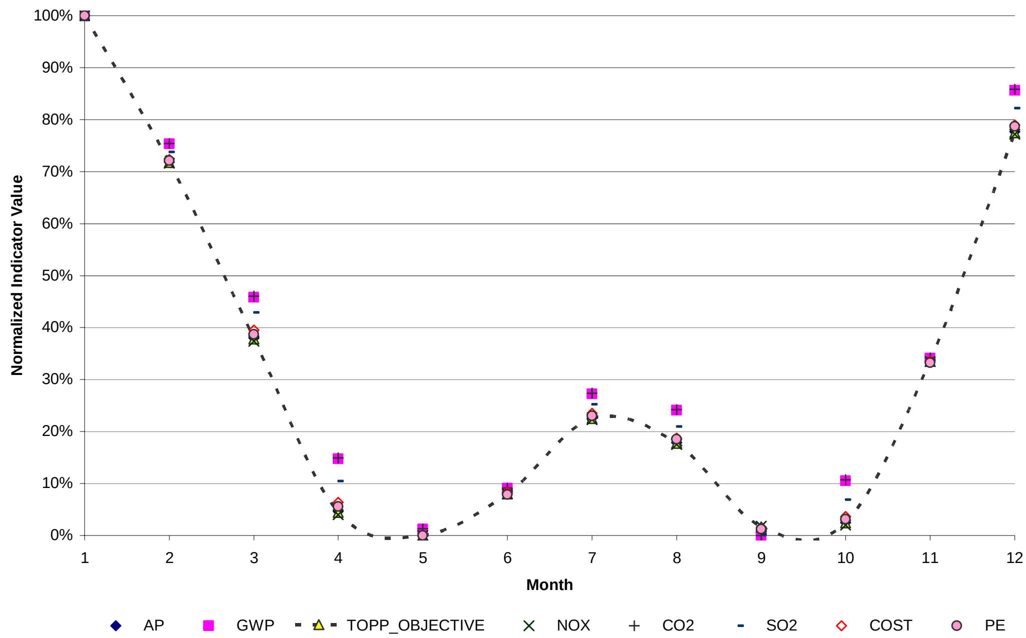



**Figure 5-105: Normalized indicator values corresponding to TOPP objective function (Hourly Model-NGCC).**

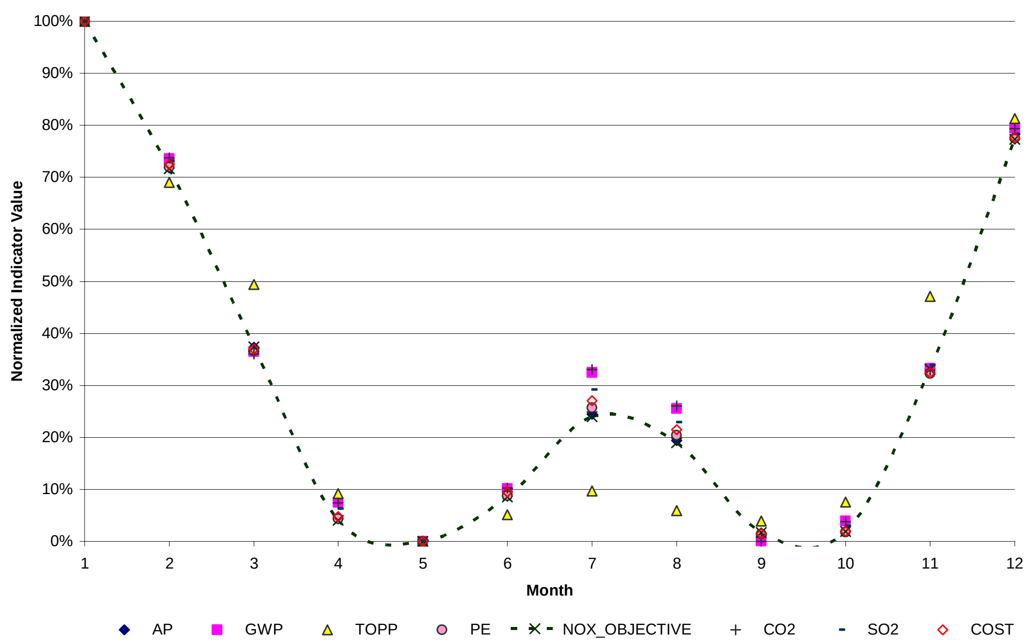



**Figure 5-106: Normalized indicator values corresponding to $NO_X$ objective function (Hourly Model-NGCC).**

**Table 5-18: Indicator values corresponding to AP objective function (Hourly Model-NGCC).**

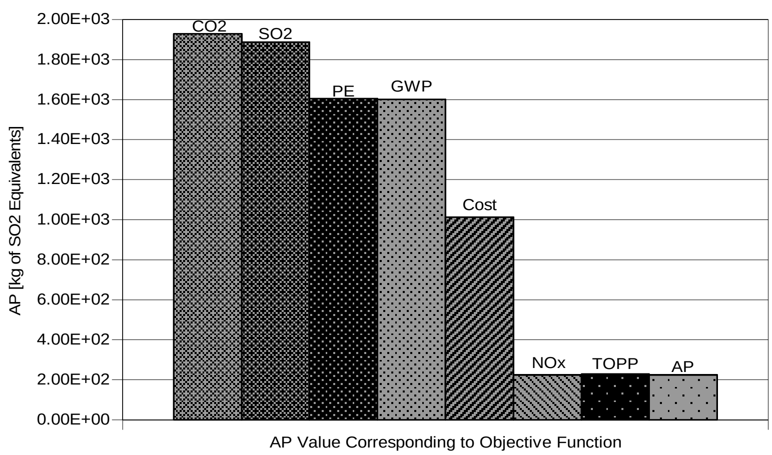
| | AP Objective | GWP | TOPP | PE | $NO_x$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 9.01E-01 | 3.65E+03 | 2.81E+00 | 1.96E+04 | 1.16E+00 | 3.55E+03 | 9.01E-02 | 8.00E+02 |
| February | 7.91E-01 | 4.26E+03 | 2.21E+00 | 1.76E+04 | 9.87E-01 | 4.17E+03 | 1.01E-01 | 7.79E+02 |
| March | 6.46E-01 | 3.69E+03 | 1.97E+00 | 1.45E+04 | 7.99E-01 | 3.61E+03 | 8.67E-02 | 6.51E+02 |
| April | 5.06E-01 | 3.24E+03 | 1.08E+00 | 1.15E+04 | 6.17E-01 | 3.19E+03 | 7.45E-02 | 5.35E+02 |
| May | 4.89E-01 | 3.17E+03 | 8.86E-01 | 1.12E+04 | 5.94E-01 | 3.12E+03 | 7.29E-02 | 5.23E+02 |
| June | 5.25E-01 | 3.31E+03 | 9.50E-01 | 1.20E+04 | 6.41E-01 | 3.26E+03 | 7.67E-02 | 5.58E+02 |
| July | 5.92E-01 | 3.66E+03 | 1.08E+00 | 1.35E+04 | 7.25E-01 | 3.60E+03 | 8.45E-02 | 6.21E+02 |
| August | 5.70E-01 | 3.57E+03 | 1.01E+00 | 1.31E+04 | 6.98E-01 | 3.51E+03 | 8.21E-02 | 6.01E+02 |
| September | 4.95E-01 | 3.17E+03 | 9.45E-01 | 1.14E+04 | 6.04E-01 | 3.12E+03 | 7.33E-02 | 5.29E+02 |
| October | 4.97E-01 | 3.19E+03 | 1.05E+00 | 1.13E+04 | 6.06E-01 | 3.14E+03 | 7.32E-02 | 5.25E+02 |
| November | 6.28E-01 | 3.59E+03 | 2.10E+00 | 1.40E+04 | 7.77E-01 | 3.51E+03 | 8.44E-02 | 6.29E+02 |
| December | 8.14E-01 | 4.36E+03 | 2.56E+00 | 1.82E+04 | 1.02E+00 | 4.26E+03 | 1.03E-01 | 7.98E+02 |
| Lowest Value | 4.89E-01 | 3.17E+03 | 8.86E-01 | 1.12E+04 | 5.94E-01 | 3.12E+03 | 7.29E-02 | 5.23E+02 |
| Highest Value | 9.01E-01 | 4.36E+03 | 2.81E+00 | 1.96E+04 | 1.16E+00 | 4.26E+03 | 1.03E-01 | 8.00E+02 |

**Table 5-19: Indicator values corresponding to TOPP objective function (Hourly Model-NGCC).**

| | AP | GWP | TOPP Objective | PE | $NO_x$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 9.45E-01 | 5.00E+03 | 1.64E+00 | 2.12E+04 | 1.18E+00 | 4.91E+03 | 1.18E-01 | 9.38E+02 |
| February | 8.17E-01 | 4.54E+03 | 1.42E+00 | 1.84E+04 | 1.02E+00 | 4.46E+03 | 1.06E-01 | 8.23E+02 |
| March | 6.62E-01 | 3.98E+03 | 1.14E+00 | 1.51E+04 | 8.15E-01 | 3.92E+03 | 9.22E-02 | 6.87E+02 |
| April | 5.10E-01 | 3.40E+03 | 8.75E-01 | 1.18E+04 | 6.18E-01 | 3.35E+03 | 7.73E-02 | 5.49E+02 |
| May | 4.89E-01 | 3.15E+03 | 8.39E-01 | 1.12E+04 | 5.95E-01 | 3.10E+03 | 7.25E-02 | 5.23E+02 |
| June | 5.25E-01 | 3.29E+03 | 9.04E-01 | 1.20E+04 | 6.42E-01 | 3.24E+03 | 7.64E-02 | 5.57E+02 |
| July | 5.92E-01 | 3.64E+03 | 1.02E+00 | 1.35E+04 | 7.26E-01 | 3.58E+03 | 8.41E-02 | 6.21E+02 |
| August | 5.70E-01 | 3.58E+03 | 9.82E-01 | 1.31E+04 | 6.98E-01 | 3.52E+03 | 8.21E-02 | 6.01E+02 |
| September | 4.96E-01 | 3.12E+03 | 8.53E-01 | 1.14E+04 | 6.05E-01 | 3.08E+03 | 7.26E-02 | 5.28E+02 |
| October | 5.00E-01 | 3.32E+03 | 8.59E-01 | 1.16E+04 | 6.07E-01 | 3.27E+03 | 7.56E-02 | 5.38E+02 |
| November | 6.42E-01 | 3.76E+03 | 1.11E+00 | 1.46E+04 | 7.92E-01 | 3.70E+03 | 8.80E-02 | 6.62E+02 |
| December | 8.43E-01 | 4.73E+03 | 1.46E+00 | 1.91E+04 | 1.05E+00 | 4.65E+03 | 1.10E-01 | 8.51E+02 |
| Lowest Value | 4.89E-01 | 3.12E+03 | 8.39E-01 | 1.12E+04 | 5.95E-01 | 3.08E+03 | 7.25E-02 | 5.23E+02 |
| Highest Value | 9.45E-01 | 5.00E+03 | 1.64E+00 | 2.12E+04 | 1.18E+00 | 4.91E+03 | 1.18E-01 | 9.38E+02 |

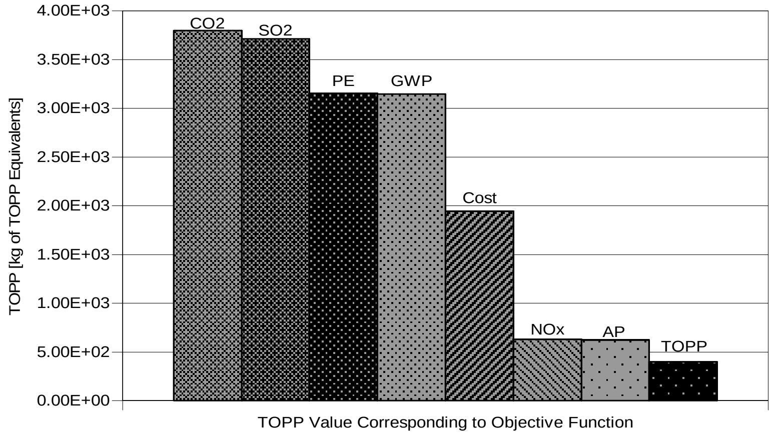
**Table 5-20: Indicator values corresponding to $NO_x$ objective function (Hourly Model-NGCC).**

| | AP | GWP | TOPP | PE | $NO_x$ Objective | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 9.10E-01 | 4.72E+03 | 2.79E+00 | 2.03E+04 | 1.14E+00 | 4.61E+03 | 1.13E-01 | 8.84E+02 |
| February | 7.91E-01 | 4.31E+03 | 2.21E+00 | 1.77E+04 | 9.86E-01 | 4.22E+03 | 1.02E-01 | 7.84E+02 |
| March | 6.46E-01 | 3.74E+03 | 1.84E+00 | 1.46E+04 | 7.98E-01 | 3.66E+03 | 8.79E-02 | 6.57E+02 |
| April | 5.07E-01 | 3.29E+03 | 1.09E+00 | 1.16E+04 | 6.16E-01 | 3.24E+03 | 7.56E-02 | 5.41E+02 |
| May | 4.89E-01 | 3.18E+03 | 9.18E-01 | 1.12E+04 | 5.94E-01 | 3.13E+03 | 7.31E-02 | 5.23E+02 |
| June | 5.25E-01 | 3.34E+03 | 1.01E+00 | 1.20E+04 | 6.41E-01 | 3.28E+03 | 7.71E-02 | 5.58E+02 |
| July | 5.92E-01 | 3.68E+03 | 1.10E+00 | 1.36E+04 | 7.25E-01 | 3.62E+03 | 8.47E-02 | 6.21E+02 |
| August | 5.70E-01 | 3.57E+03 | 1.03E+00 | 1.31E+04 | 6.98E-01 | 3.52E+03 | 8.22E-02 | 6.01E+02 |
| September | 4.96E-01 | 3.18E+03 | 9.92E-01 | 1.14E+04 | 6.03E-01 | 3.13E+03 | 7.35E-02 | 5.29E+02 |
| October | 4.97E-01 | 3.24E+03 | 1.06E+00 | 1.14E+04 | 6.04E-01 | 3.19E+03 | 7.42E-02 | 5.30E+02 |
| November | 6.29E-01 | 3.69E+03 | 1.80E+00 | 1.42E+04 | 7.75E-01 | 3.62E+03 | 8.66E-02 | 6.40E+02 |
| December | 8.15E-01 | 4.40E+03 | 2.44E+00 | 1.82E+04 | 1.02E+00 | 4.31E+03 | 1.04E-01 | 8.03E+02 |
| Lowest Value | 4.89E-01 | 3.18E+03 | 9.18E-01 | 1.12E+04 | 5.94E-01 | 3.13E+03 | 7.31E-02 | 5.23E+02 |
| Highest Value | 9.10E-01 | 4.72E+03 | 2.79E+00 | 2.03E+04 | 1.14E+00 | 4.61E+03 | 1.13E-01 | 8.84E+02 |



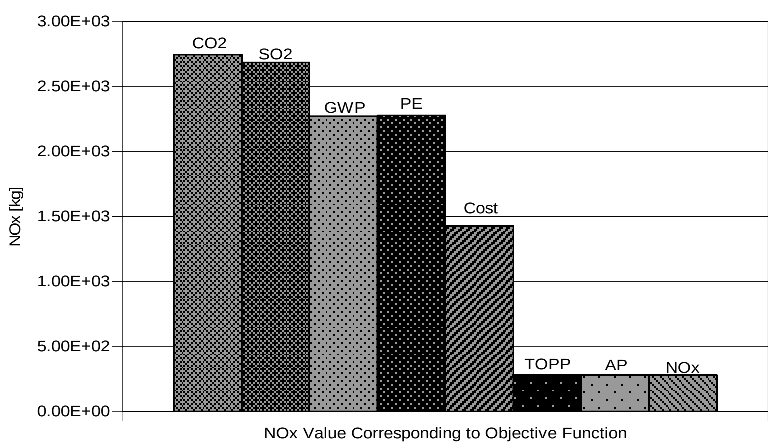

| | AP Value Corresponding to Objective Function |
|---|---|
| CO2 Objective Function | 1.93E+03 |
| SO2 Objective Function | 1.89E+03 |
| PE Objective Function | 1.61E+03 |
| GWP Objective Function | 1.60E+03 |
| Cost Objective Function | 1.01E+03 |
| NOx Objective Function | 2.25E+02 |
| TOPP Objective Function | 2.29E+02 |
| AP Objective Function | 2.25E+02 |

Figure 5-107: Indicator values corresponding to AP objective function (Yearly Model-NGCC).




| | TOPP Value Corresponding to Objective Function |
|---|---|
| CO2 Objective Function | 3.80E+03 |
| SO2 Objective Function | 3.71E+03 |
| PE Objective Function | 3.15E+03 |
| GWP Objective Function | 3.15E+03 |
| Cost Objective Function | 1.94E+03 |
| NOx Objective Function | 6.29E+02 |
| AP Objective Function | 6.20E+02 |
| TOPP Objective Function | 3.95E+02 |

**Figure 5-108: Indicator values corresponding to TOPP objective function (Yearly Model-NGCC).**




| | NOx Value Corresponding to Objective Function |
|---|---|
| CO2 Objective Function | 2.74E+03 |
| SO2 Objective Function | 2.68E+03 |
| GWP Objective Function | 2.27E+03 |
| PE Objective Function | 2.28E+03 |
| Cost Objective Function | 1.43E+03 |
| TOPP Objective Function | 2.82E+02 |
| AP Objective Function | 2.78E+02 |
| NOx Objective Function | 2.78E+02 |

**Figure 5-109: Indicator values corresponding to $NO_x$ objective function (Yearly Model-NGCC).**

#### 5.3.2.3 Minimizing $SO_2$

When using the *hourly LCA Optimization Model* to minimize the $SO_2$ objective function in the 12 average days in the months of January through December, the results of the optimization model showed that primarily the NGCC and the ICE cogeneration systems were used to meet the power demand of the building. Unlike the results obtained from the *Hourly LCA Optimization Model* to minimize the $SO_2$ objective function for the first problem set with the average electric grid option, where the ICE and the MT cogeneration systems supplied all the energy demand of the building, the NGCC which has a comparatively similar $SO_2$ emission factor to the cogeneration systems was preferable in this case. Figures 5-110 and 5-111 show the percent power supply and percent heating supply of the energy systems in each day of the months of January through December, respectively. The ICE cogeneration system supplied more than 50% of the electrical demand and the NGCC supplied the remaining electrical demand whereas the MT cogeneration system was used minimally to supplement some power requirements in certain days. The thermal demand was supplied mainly by the cogenerated heat from the ICE cogeneration system while the gas boiler was only used in heating months to meet partial of the heating demand. The absorption chiller was used to meet most of the cooling demand throughout the 12 days and the electric chiller was used partially in the cooling months, as shown in Figure 5-112.

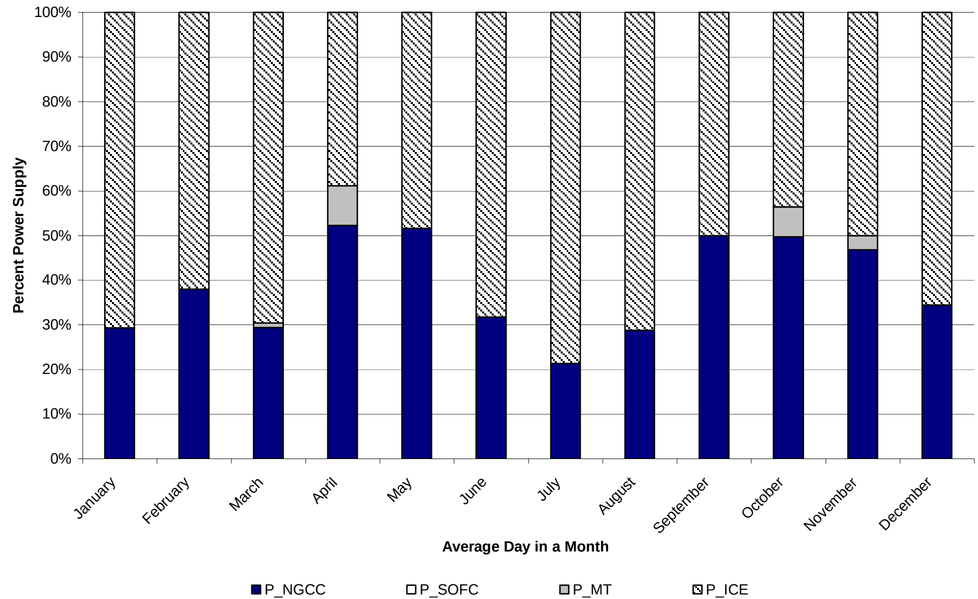



**Figure 5-110: Percent power supply from energy systems: Hourly Model for min $SO_2$ (NGCC).**

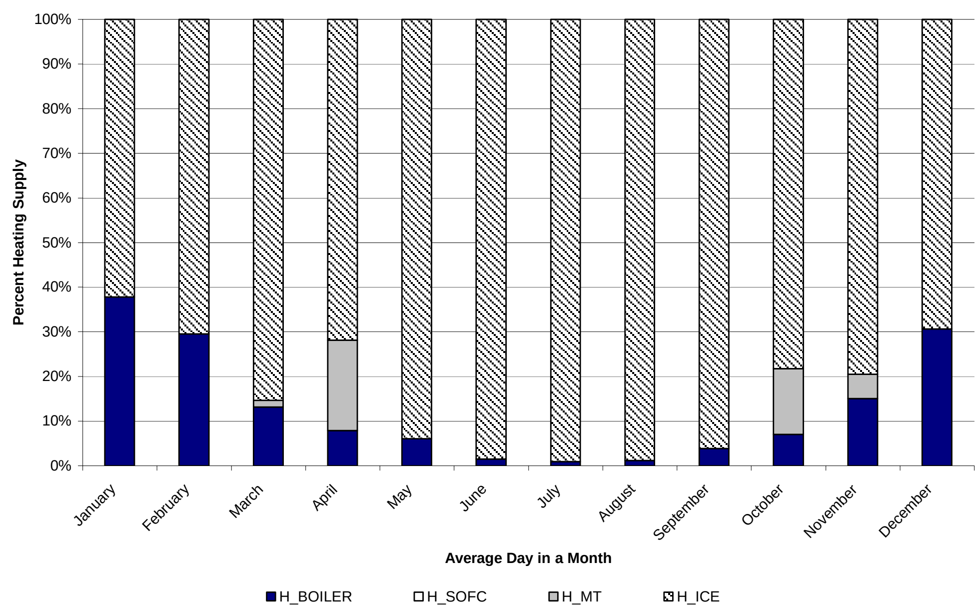



**Figure 5-111: Percent heating supply from energy systems: Hourly Model for min $SO_2$ (NGCC).**

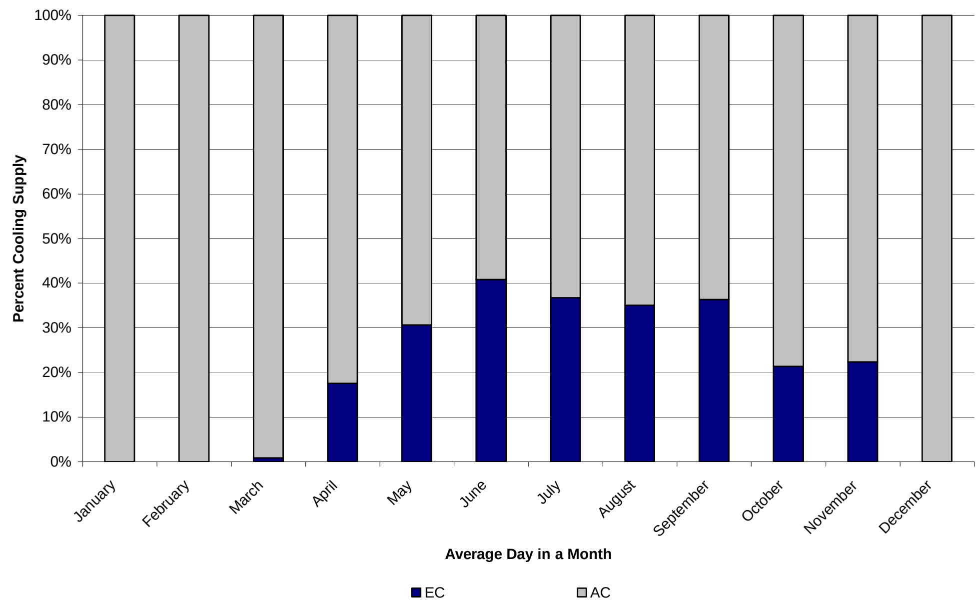



**Figure 5-112: Percent cooling supply from energy systems: Hourly Model for min $SO_2$ (NGCC).**

When using the *Simplified Yearly LCA Optimization Model* to minimize $SO_2$ in the year, the results of the optimization model was generally similar to that obtained from the *Hourly LCA Optimization Model* for minimizing $SO_2$. Figures 5-113 and 5-114 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing $SO_2$, respectively. Figures 5-115 and 5-116 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing $SO_2$, respectively. Figures 5-117 and 5-118 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing $SO_2$, respectively. The graphs indicate the similarity in operational strategies and systems used to meet the energy demand of the building.

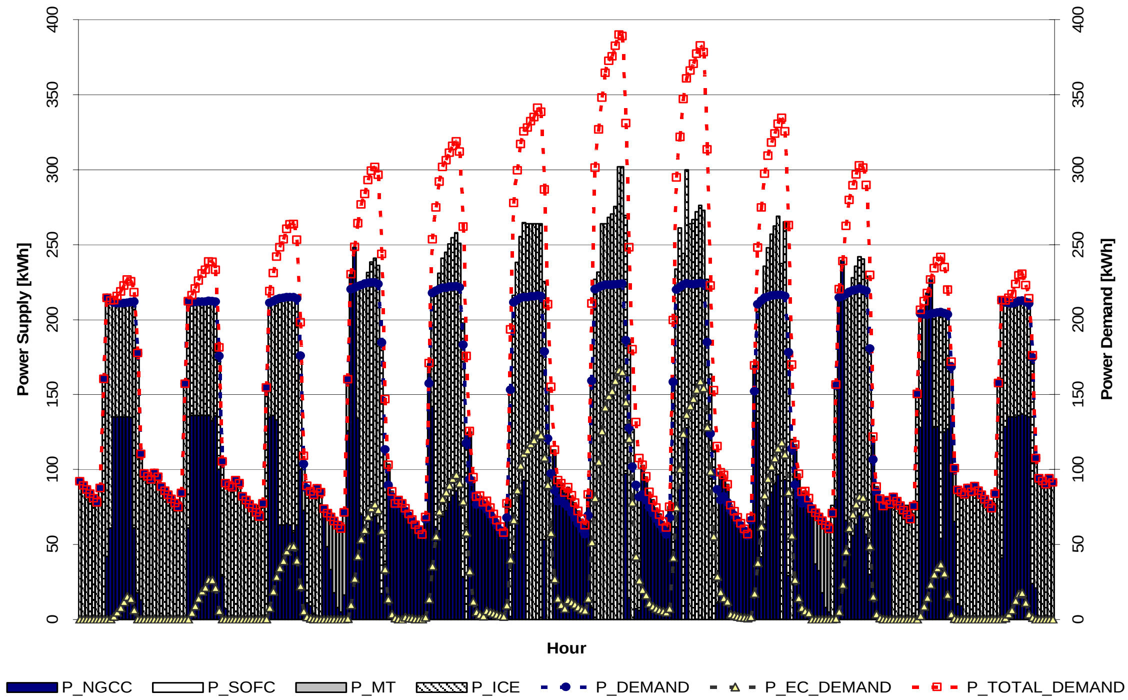



**Figure 5-113: Power supply: solution from Hourly model (NGCC) for min $SO_2$.**

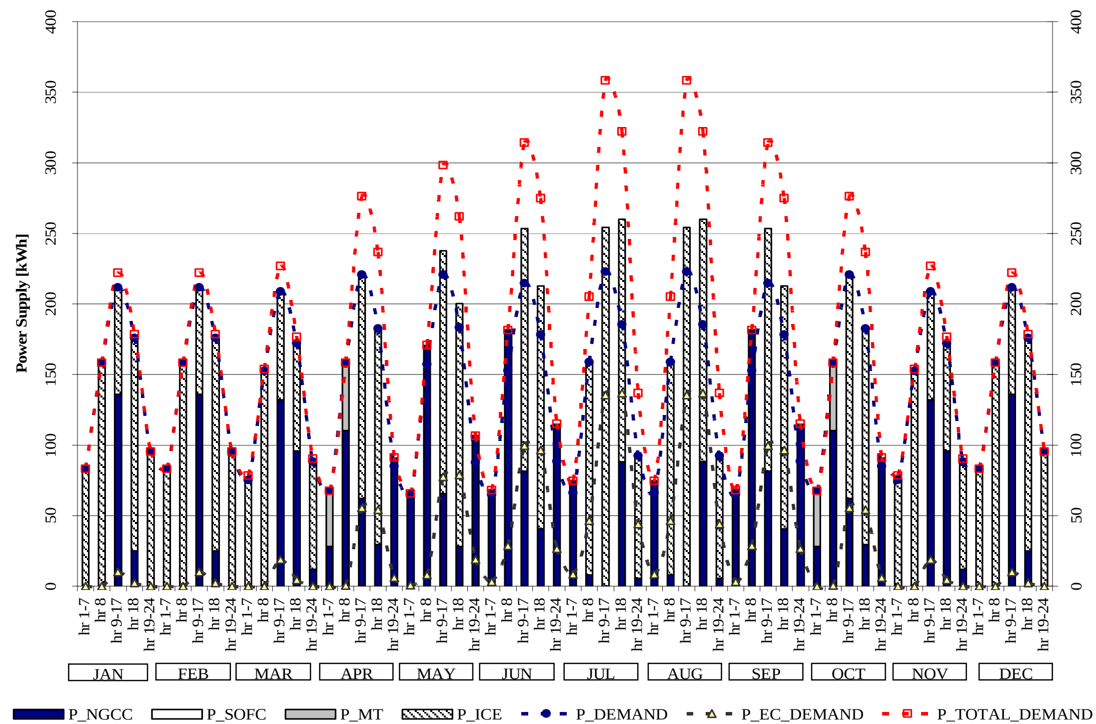



**Figure 5-114: Power supply: solution from Yearly model (NGCC) for min $SO_2$.**

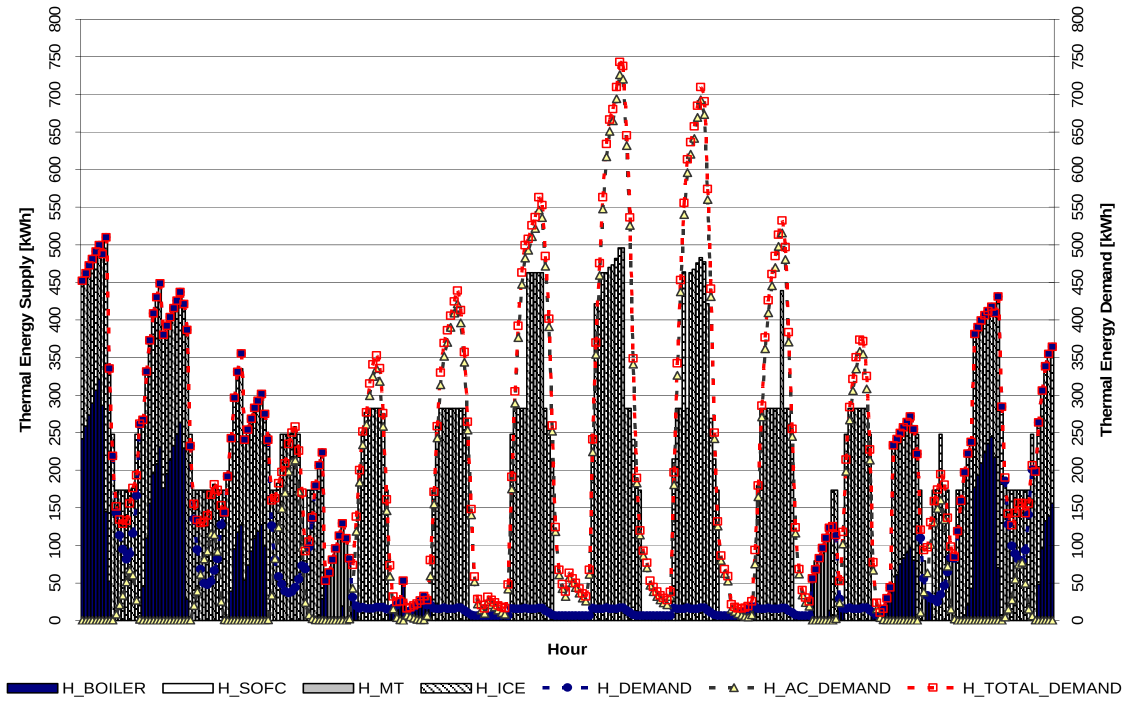



**Figure 5-115: Heating supply: solution from Hourly Model (NGCC) for min $SO_2$.**

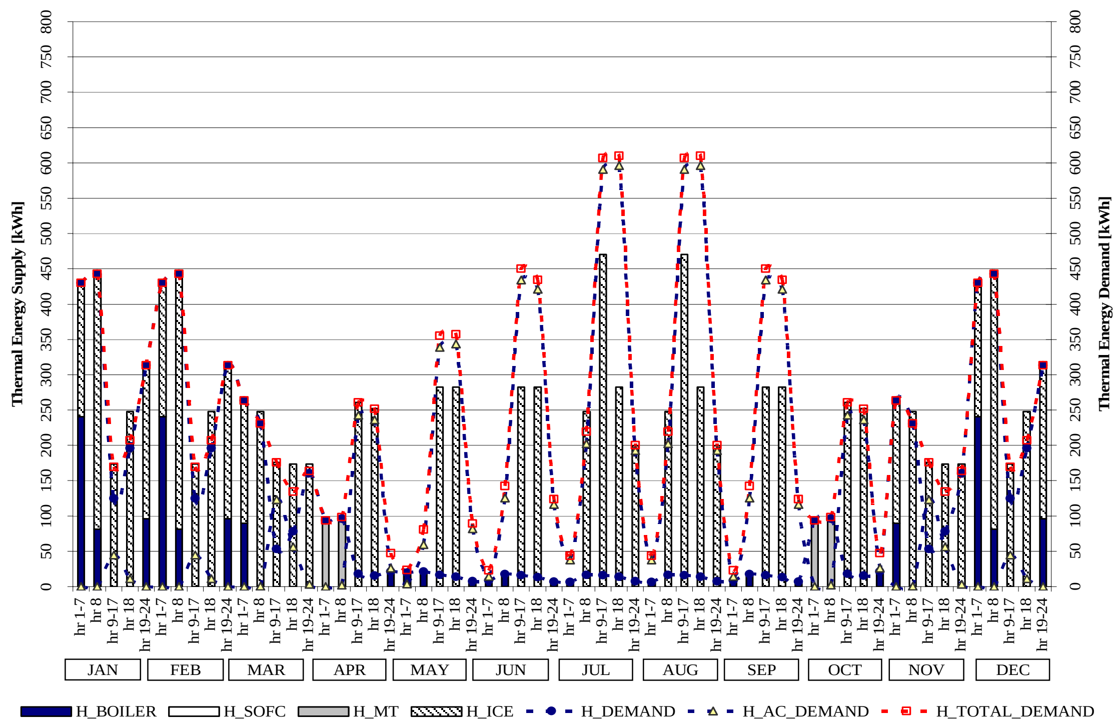



**Figure 5-116: Heating supply: solution from Yearly Model (NGCC) for min $SO_2$.**

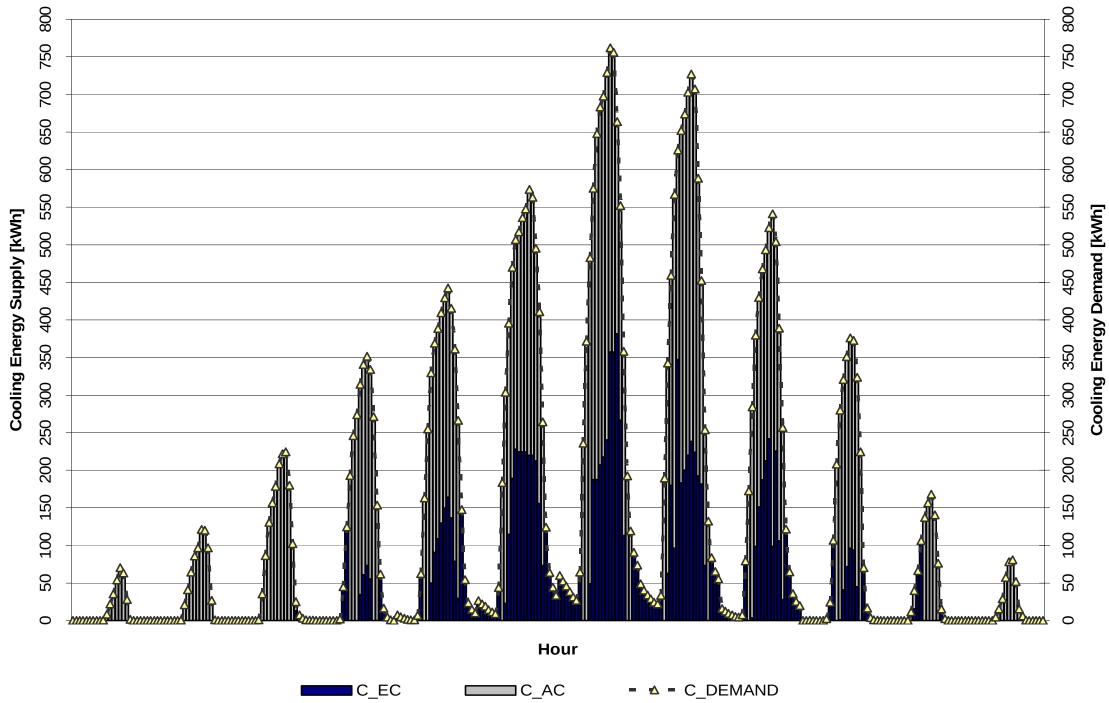



**Figure 5-117: Cooling supply: solution from Hourly Model (NGCC) for min $SO_2$.**

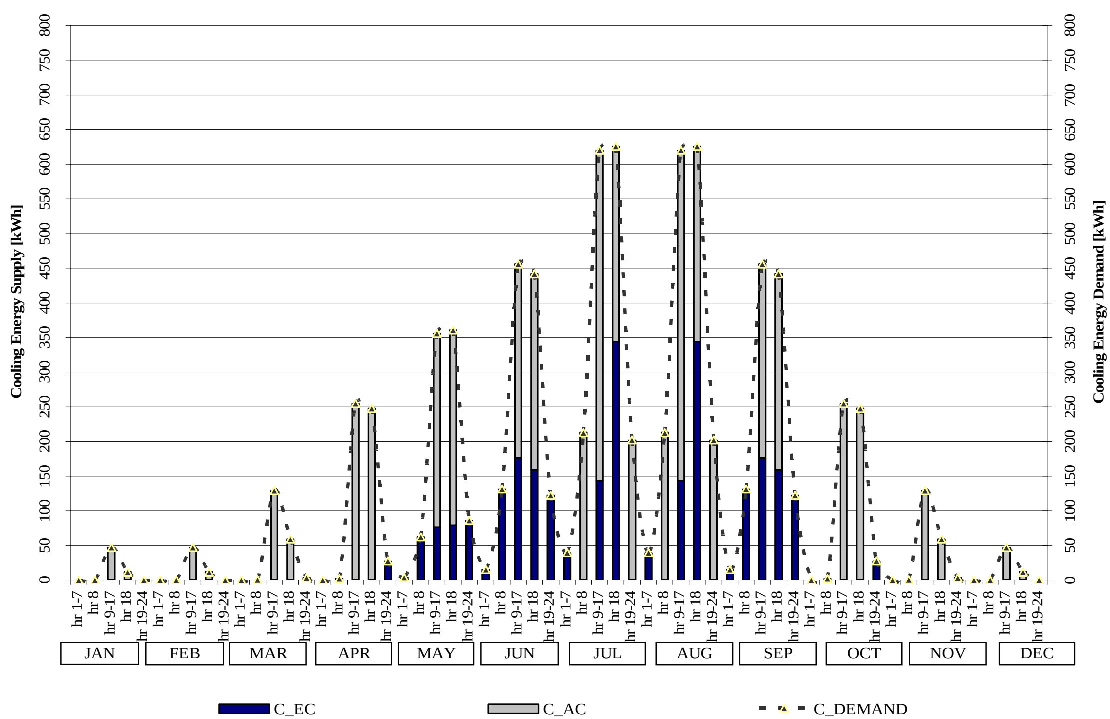



**Figure 5-118: Cooling supply: solution from Yearly model (NGCC) for min $SO_2$.**

When minimizing $SO_2$, the lowest values of the objective function (less than 10% of the maximum value) were obtained in the transitional months of April, May, September, and October as well as November and then the highest values of the objective functions (more than 60% of the maximum value) were obtained in the heating months of January, February, and December. The objective functions values, which laid between 10% and 40% of the maximum value, occurred in the cooling months of June, July, and August as well as March. This was mainly because in the heating months the total energy demand is higher than the rest of the months; therefore the emissions are higher in those months. Figure 5-119 show the normalized objective function values of $SO_2$ in the 12 average days of January through December and the calculated values of the indicators corresponding to the minimum objective values. Table 5-21 shows the values of the $SO_2$ objective function and the corresponding indicator values.

The results obtained from the *Simplified Yearly LCA Optimization Model* generated the total values of the objective function and the corresponding values of the other indicators. Figure 5-120 shows the values of $SO_2$ expressed in *kg* corresponding to each objective function, respectively. Generally, when minimizing the $SO_2$, $CO_2$, GWP, PE and cost, the values of $SO_2$ obtained were approximately equal, but the values of the $SO_2$ increased about 78% when minimizing TOPP, AP and $NO_x$. These trends reflect the characteristics of the energy systems used when minimizing each of the objective functions. Since the SOFC and MT cogeneration systems have relatively higher $SO_2$ emission factors compared to the ICE cogeneration system and the NGCC, the resultant $SO_2$ emissions from their use was higher when minimizing TOPP, AP and $NO_x$ whereas the ICE cogeneration system and the NGCC were used when minimizing $SO_2$, $CO_2$, GWP, PE and cost, resulting in lower $SO_2$ emissions.

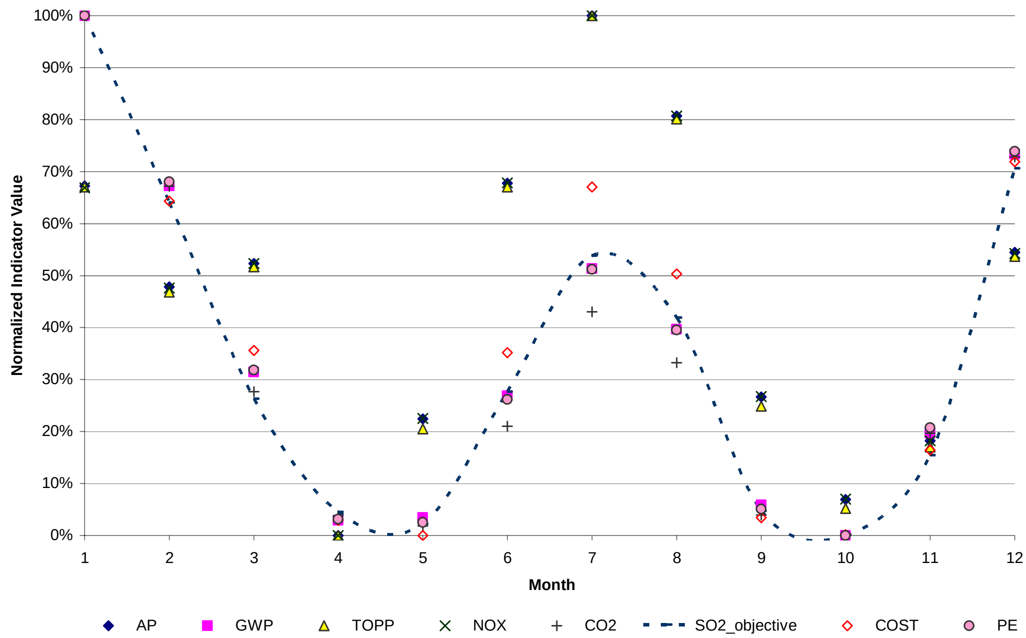
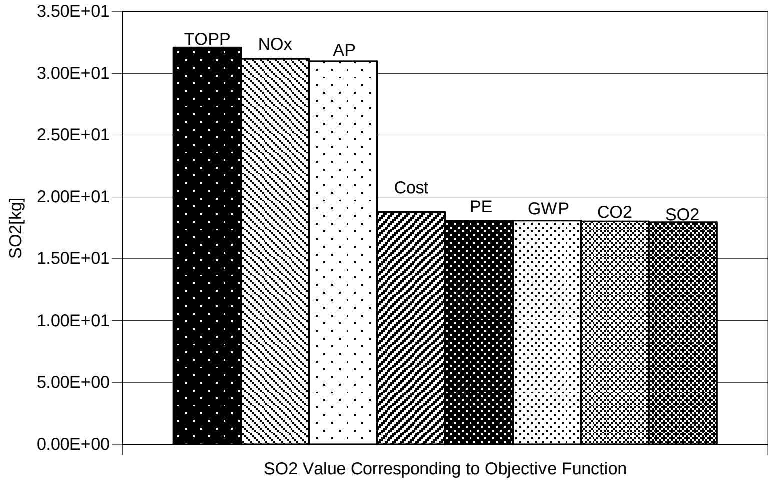



**Figure 5-119: Normalized indicator values corresponding to $SO_2$ objective function (Hourly Model-NGCC).**

**Table 5-21: Indicator values corresponding to $SO_2$ objective function (Hourly Model-NGCC).**

| | AP | GWP | TOPP | $SO_2$ Objective | PE | $NO_x$ | $CO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 6.06E+00 | 2.96E+03 | 1.20E+01 | 6.20E-02 | 1.50E+04 | 8.62E+00 | 2.72E+03 | 5.06E+02 |
| February | 5.38E+00 | 2.62E+03 | 1.06E+01 | 5.53E-02 | 1.33E+04 | 7.64E+00 | 2.41E+03 | 4.47E+02 |
| March | 5.54E+00 | 2.25E+03 | 1.09E+01 | 4.81E-02 | 1.15E+04 | 7.88E+00 | 2.04E+03 | 4.00E+02 |
| April | 3.69E+00 | 1.96E+03 | 7.36E+00 | 4.40E-02 | 9.98E+03 | 5.24E+00 | 1.81E+03 | 3.46E+02 |
| May | 4.48E+00 | 1.96E+03 | 8.76E+00 | 4.36E-02 | 9.94E+03 | 6.37E+00 | 1.79E+03 | 3.41E+02 |
| June | 6.08E+00 | 2.20E+03 | 1.19E+01 | 4.84E-02 | 1.12E+04 | 8.66E+00 | 1.97E+03 | 3.99E+02 |
| July | 7.22E+00 | 2.46E+03 | 1.42E+01 | 5.33E-02 | 1.25E+04 | 1.03E+01 | 2.18E+03 | 4.52E+02 |
| August | 6.54E+00 | 2.34E+03 | 1.28E+01 | 5.11E-02 | 1.19E+04 | 9.32E+00 | 2.09E+03 | 4.24E+02 |
| September | 4.63E+00 | 1.99E+03 | 9.06E+00 | 4.41E-02 | 1.01E+04 | 6.59E+00 | 1.81E+03 | 3.47E+02 |
| October | 3.93E+00 | 1.93E+03 | 7.72E+00 | 4.32E-02 | 9.82E+03 | 5.59E+00 | 1.78E+03 | 3.42E+02 |
| November | 4.33E+00 | 2.13E+03 | 8.52E+00 | 4.61E-02 | 1.09E+04 | 6.16E+00 | 1.96E+03 | 3.69E+02 |
| December | 5.61E+00 | 2.68E+03 | 1.10E+01 | 5.65E-02 | 1.36E+04 | 7.98E+00 | 2.46E+03 | 4.60E+02 |
| Lowest Value | 3.69E+00 | 1.93E+03 | 7.36E+00 | 4.32E-02 | 9.82E+03 | 5.24E+00 | 1.78E+03 | 3.41E+02 |
| Highest Value | 7.22E+00 | 2.96E+03 | 1.42E+01 | 6.20E-02 | 1.50E+04 | 1.03E+01 | 2.72E+03 | 5.06E+02 |




| | *SO2 Value Corresponding to Objective Function* |
|---|---|
| *TOPP Objective Function* | *3.21E+01* |
| *NOx Objective Function* | *3.12E+01* |
| *AP Objective Function* | *3.10E+01* |
| *Cost Objective Function* | *1.88E+01* |
| *PE Objective Function* | *1.81E+01* |
| *GWP Objective Function* | *1.81E+01* |
| *CO2 Objective Function* | *1.80E+01* |
| *SO2 Objective Function* | *1.80E+01* |

**Figure 5-120: Indicator values corresponding to $SO_2$ objective function (Yearly Model-NGCC).**

#### 5.3.2.4 Minimizing Primary Energy Consumption

When using the *Hourly LCA Optimization Model* to minimize PE in the 12 average days in the 12 months, the NGCC was used mainly to supply power in the 12 days and the remaining of the power demand was supplied mainly by the ICE cogeneration system and to a lesser extent by the MT cogeneration system. The use of the NGCC was lower when the thermal demand was higher, when the ICE and MT cogeneration systems supplied higher proportion of power. The thermal demand was met mainly by the ICE cogeneration system in the months of May through September. The MT cogeneration systems contributed a higher percentage of the thermal demand in the months of April and October in addition to the ICE cogeneration system. The gas boiler use was minimal in those months and increased during the heating months to supplement the heat supplied by the ICE and MT cogeneration system in order to meet the heating requirement. Cooling was supplied mainly by the electric chillers and partially by the absorption chillers. However during the months of April and October the percentage absorption chiller use was higher corresponding to the higher use of the heat supplied by the MT and ICE cogeneration systems. Figures 5-121, 5-122 and 5-123 show the percent power, heating and cooling supply of the energy systems in the 12 average days in the months of January through December.

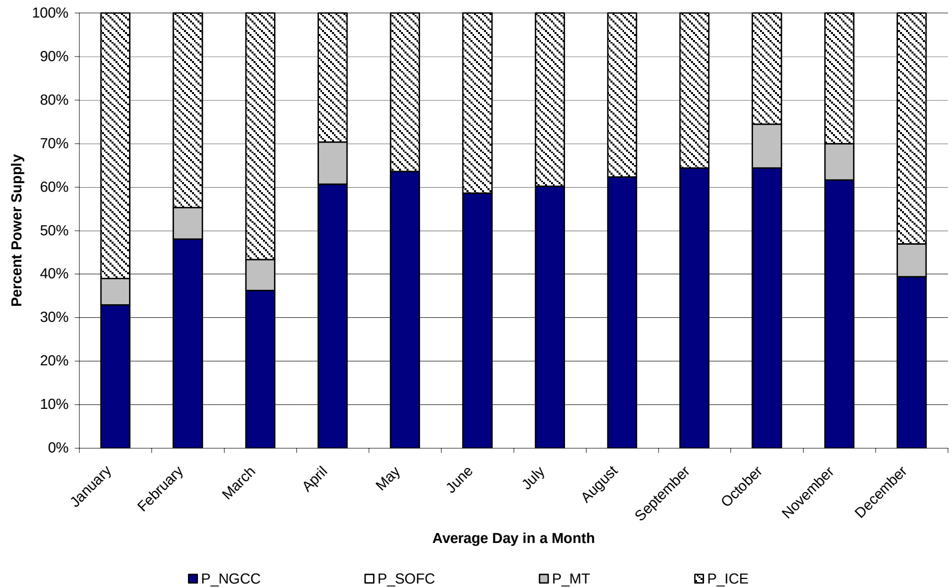



**Figure 5-121: Percent power supply from energy systems: Hourly Model for min PE (NGCC).**

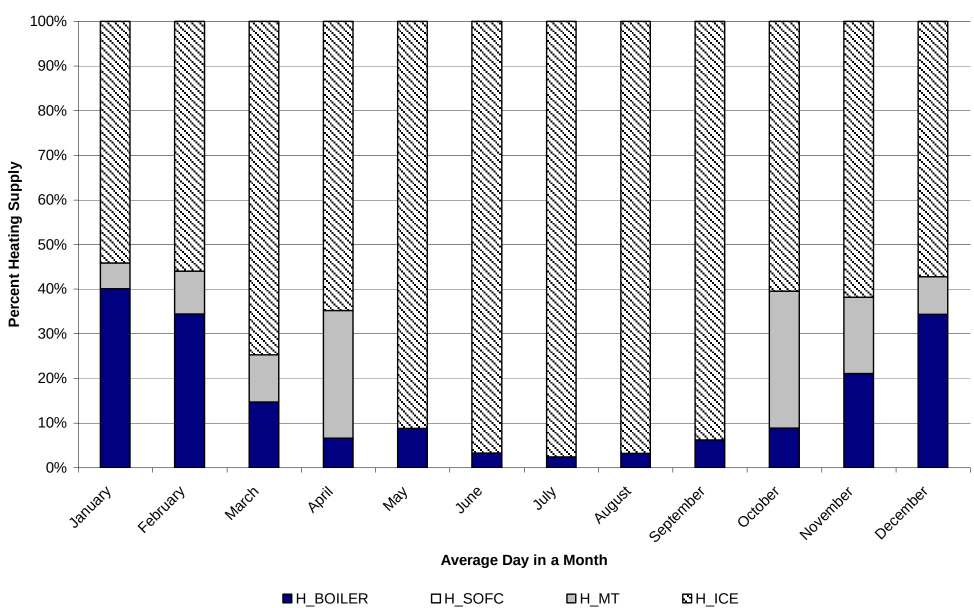



**Figure 5-122: Percent heating supply from energy systems: Hourly Model for min PE (NGCC).**

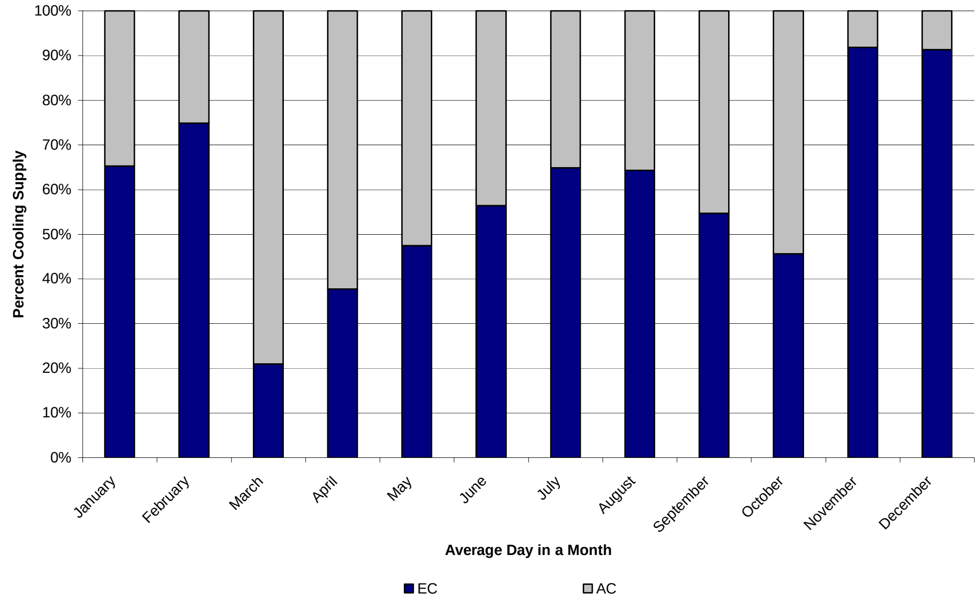



**Figure 5-123: Percent cooling supply from energy systems: Hourly Model for min PE (NGCC).**

When using the *Simplified Yearly LCA Optimization Model* to minimize the PE in the year, the results were generally similar to those obtained from the *Hourly LCA Optimization Model*. Figures 5-124 and 5-125 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* and for minimizing PE, respectively. Figures 5-126 and 5-127 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing PE, respectively. Figures 5-128 and 5-129 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified Yearly LCA Optimization Model* for minimizing PE, respectively. The graphs indicate the similarity in operational trends of the building.

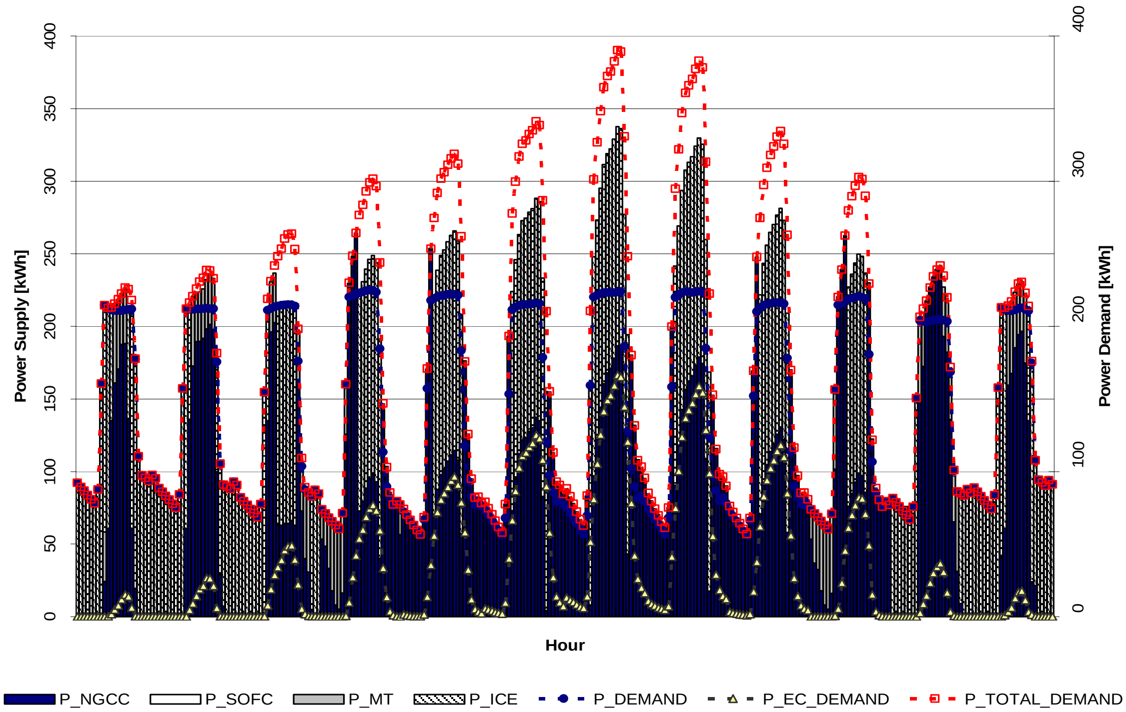



**Figure 5-124: Power supply: solution from Hourly Model (NGCC) for min PE.**

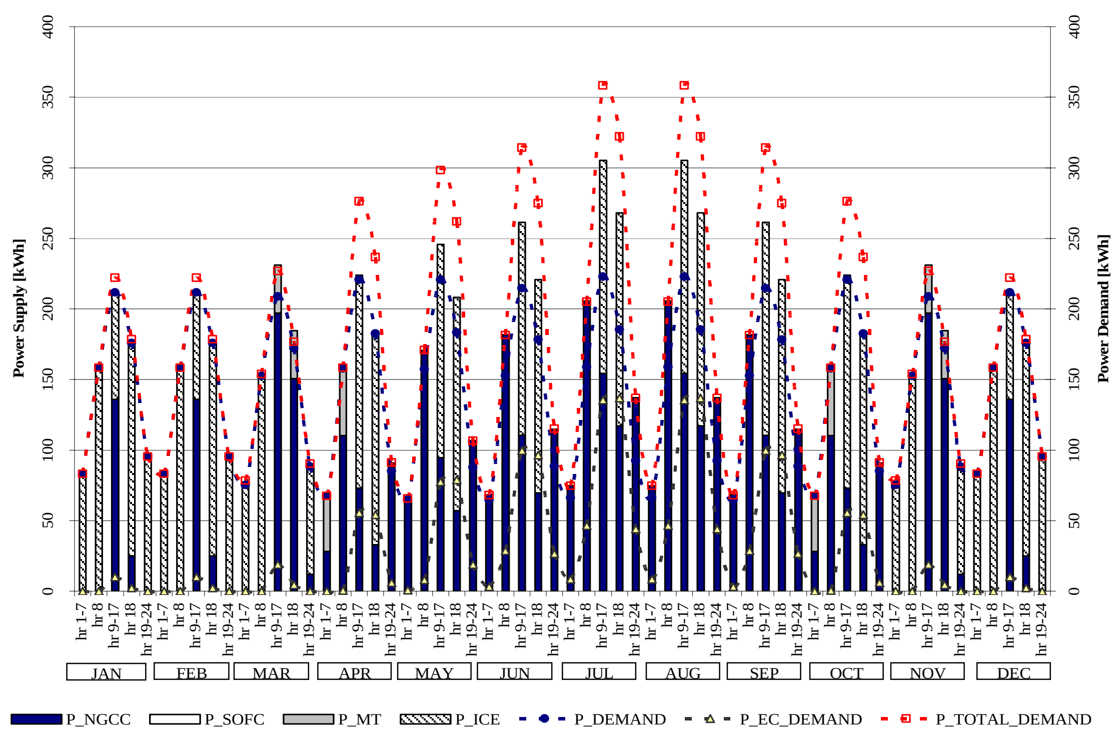



**Figure 5-125: Power supply: solution from Yearly Model (NGCC) for min PE.**

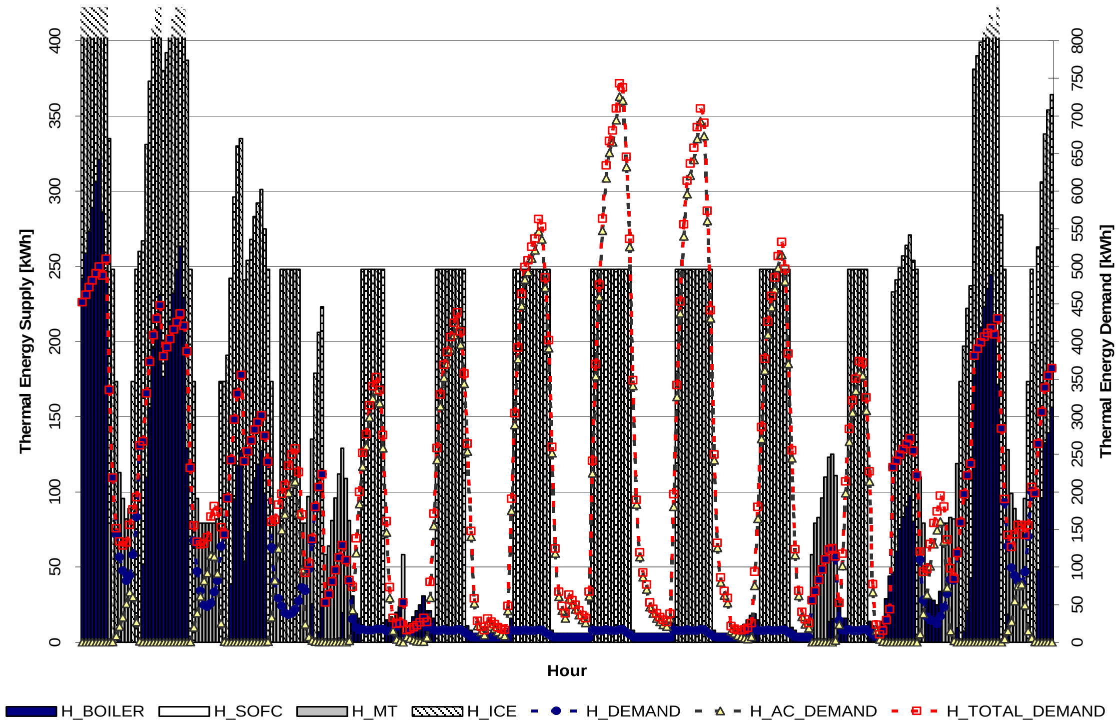



**Figure 5-126: Heating supply: solution from Hourly Model (NGCC) for min PE.**

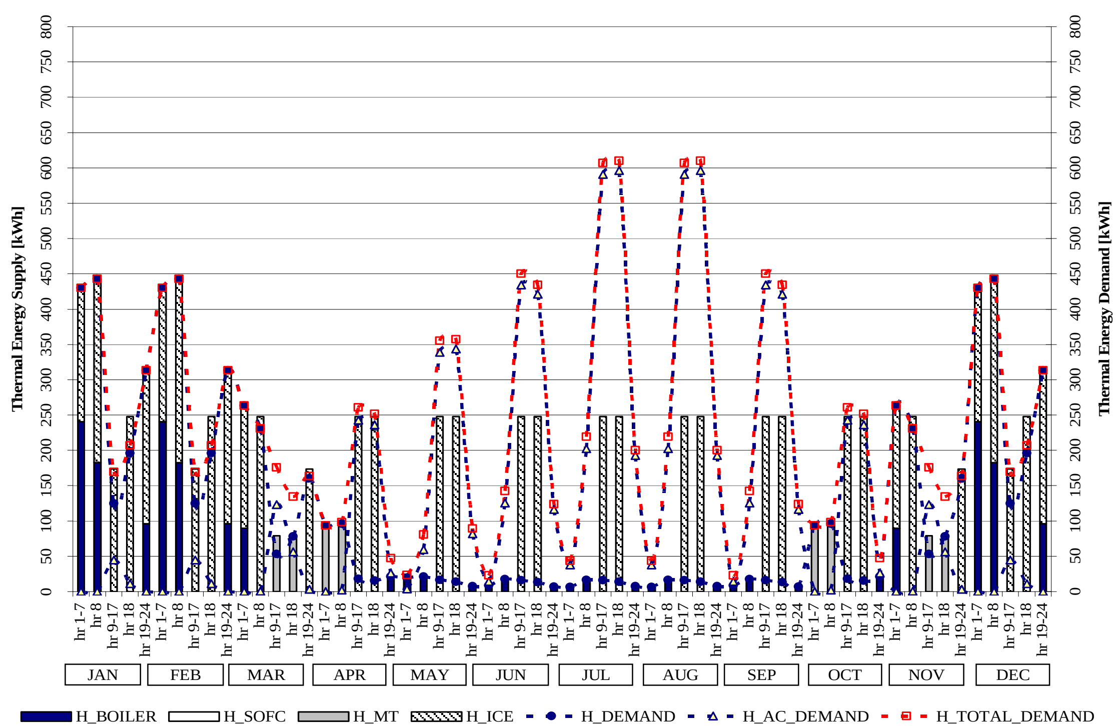



**Figure 5-127: Heating supply: solution from Yearly model (NGCC) for min PE.**

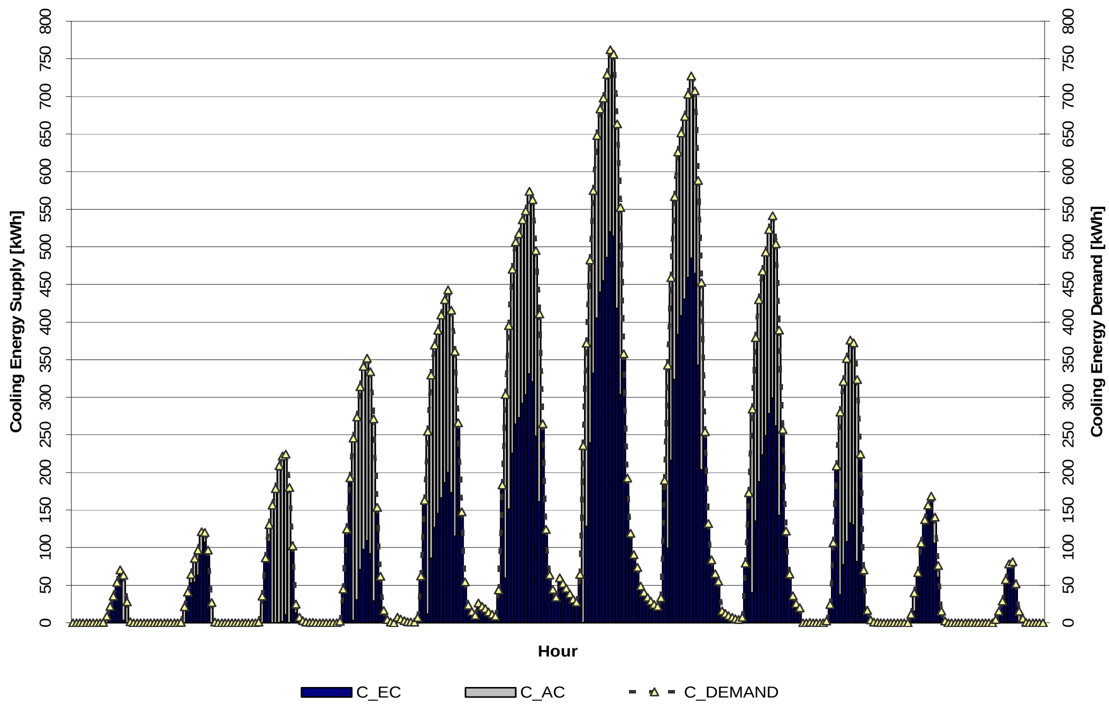



**Figure 5-128: Cooling supply: solution from Hourly Model (NGCC) for min PE.**

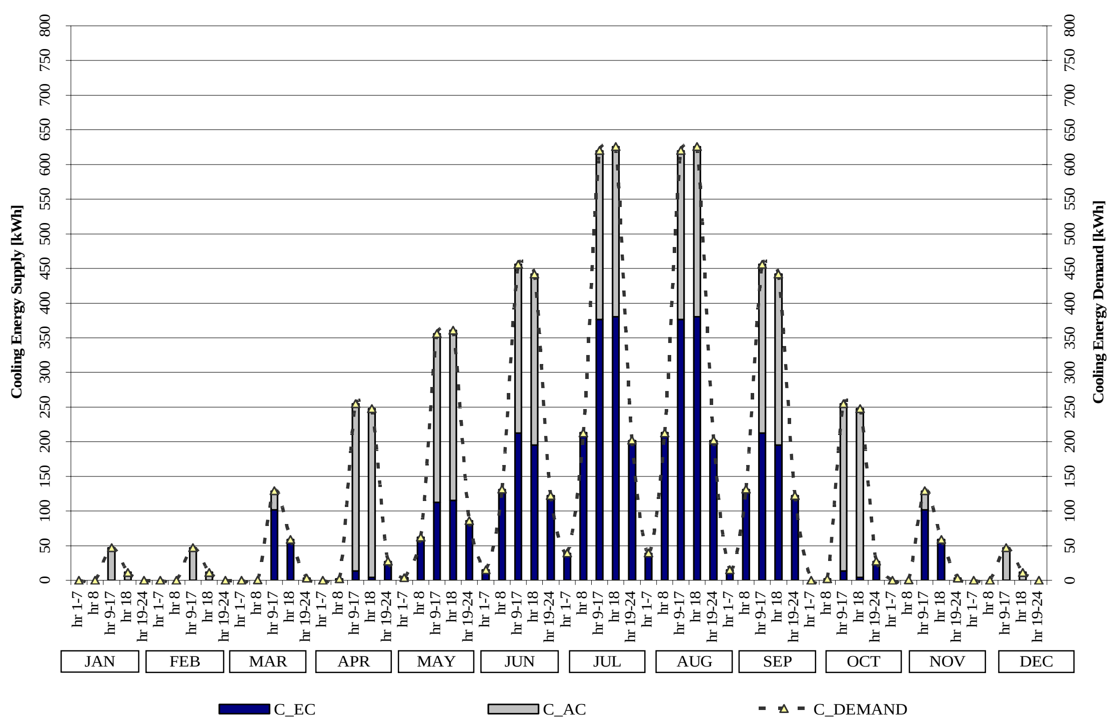



**Figure 5-129: Cooling supply: solution from Yearly Model (NGCC) for min PE.**

When using the Hourly LCA Optimization Model to minimize PE in the 12 average days in the 12 months, generally the values of the objective function decreased from January to low values in April and May and then started to increase in June and July and decreased to the minimum value in October and then increased again in November and December. Table 5-22 shows the values of the objective function and corresponding indicator values. If the highest value of the objective function is considered as 100%, then lowest values of the objective functions (less than 10% of the maximum value) were attained in the transitional months of April, May, September, and October and then the highest values of the objective functions (greater than 60% of the maximum value) were obtained in the heating months of January, February, and December. The objective function values, which laid between 10% and 40% of the maximum value, occurred in the cooling months of June, July, and August as well as the transitional months of March and November. Figure 5-130 shows the normalized objective function values in the 12 average days of January through December and the corresponding values of the other indicators.

The results obtained from the *Simplified Yearly LCA Optimization Model*, generated the total values of the objective function and the corresponding values of the other indicators. Figure 5-131 shows the values of PE in *kWh* corresponding to each objective function obtained from the *Simplified Yearly LCA Optimization Model* results. When minimizing the PE, GWP, $CO_2$, $SO_2$ and cost, the values of PE obtained were approximately in the same range, but the values of the PE increased by about 25% when minimizing TOPP, AP and $NO_x$. This was mainly because the PE emission factor of the MT cogeneration system, which was used to supply part of the energy demand when minimizing TOPP, AP and $NO_x$, is relatively higher than the PE emission factors of the other energy systems.

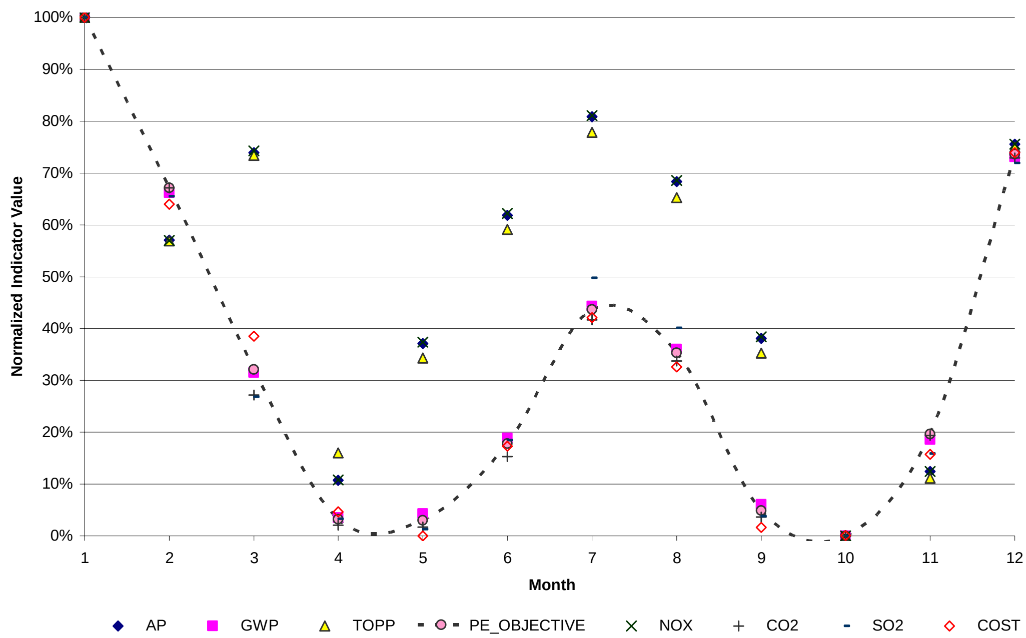
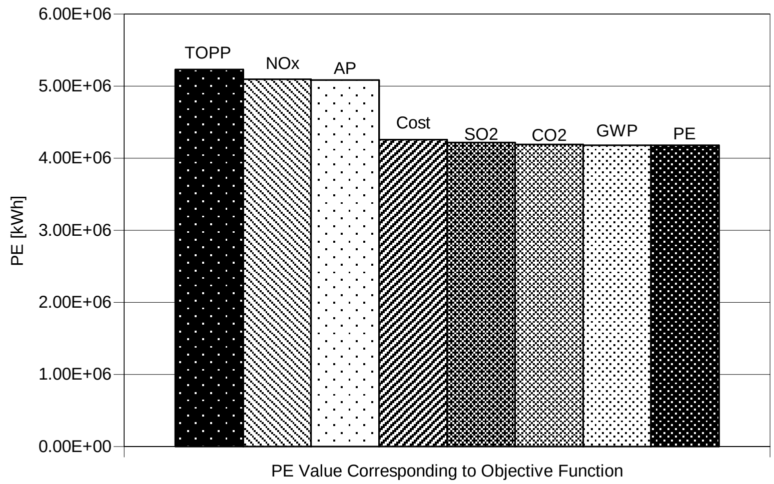



**Figure 5-130: Normalized indicator values corresponding to PE objective function (Hourly Model-NGCC).**

**Table 5-22: Indicator values corresponding to PE objective function (Hourly Model-NGCC).**

| | AP | GWP | TOPP | PE Objective | $NO_X$ | $CO_2$ | $SO_2$ | COST |
|---|---|---|---|---|---|---|---|---|
| January | 5.47E+00 | 2.93E+03 | 1.08E+01 | 1.49E+04 | 7.76E+00 | 2.72E+03 | 6.25E-02 | 5.06E+02 |
| February | 4.39E+00 | 2.59E+03 | 8.68E+00 | 1.32E+04 | 6.22E+00 | 2.41E+03 | 5.60E-02 | 4.43E+02 |
| March | 4.81E+00 | 2.23E+03 | 9.50E+00 | 1.14E+04 | 6.84E+00 | 2.04E+03 | 4.87E-02 | 3.99E+02 |
| April | 3.22E+00 | 1.94E+03 | 6.66E+00 | 9.91E+03 | 4.57E+00 | 1.81E+03 | 4.42E-02 | 3.39E+02 |
| May | 3.89E+00 | 1.95E+03 | 7.57E+00 | 9.90E+03 | 5.52E+00 | 1.81E+03 | 4.39E-02 | 3.31E+02 |
| June | 4.51E+00 | 2.10E+03 | 8.79E+00 | 1.07E+04 | 6.41E+00 | 1.93E+03 | 4.71E-02 | 3.61E+02 |
| July | 4.98E+00 | 2.36E+03 | 9.72E+00 | 1.20E+04 | 7.08E+00 | 2.18E+03 | 5.30E-02 | 4.05E+02 |
| August | 4.67E+00 | 2.28E+03 | 9.10E+00 | 1.16E+04 | 6.63E+00 | 2.10E+03 | 5.12E-02 | 3.88E+02 |
| September | 3.91E+00 | 1.97E+03 | 7.61E+00 | 1.00E+04 | 5.56E+00 | 1.83E+03 | 4.44E-02 | 3.34E+02 |
| October | 2.96E+00 | 1.91E+03 | 5.87E+00 | 9.75E+03 | 4.18E+00 | 1.79E+03 | 4.36E-02 | 3.31E+02 |
| November | 3.27E+00 | 2.10E+03 | 6.42E+00 | 1.08E+04 | 4.63E+00 | 1.97E+03 | 4.66E-02 | 3.59E+02 |
| December | 4.85E+00 | 2.66E+03 | 9.57E+00 | 1.35E+04 | 6.89E+00 | 2.47E+03 | 5.72E-02 | 4.60E+02 |
| Lowest Value | 2.96E+00 | 1.91E+03 | 5.87E+00 | 9.75E+03 | 4.18E+00 | 1.79E+03 | 4.36E-02 | 3.31E+02 |
| Highest Value | 5.47E+00 | 2.93E+03 | 1.08E+01 | 1.49E+04 | 7.76E+00 | 2.72E+03 | 6.25E-02 | 5.06E+02 |




| | *PE Value Corresponding to Objective Function* |
|---|---|
| *TOPP Objective Function* | *5.23E+06* |
| *NOx Objective Function* | *5.10E+06* |
| *AP Objective Function* | *5.08E+06* |
| *Cost Objective Function* | *4.26E+06* |
| *SO2 Objective Function* | *4.22E+06* |
| *CO2 Objective Function* | *4.19E+06* |
| *GWP Objective Function* | *4.18E+06* |
| *PE Objective Function* | *4.18E+06* |

**Figure 5-131: Indicator values corresponding to $CO_2$ objective function (Yearly Model-NGCC).**

### 5.3.2.5 Minimizing Cost

When using the *Hourly LCA Optimization Model* to minimize cost, the results of the optimization model showed that the NGCC power plant was used primarily to meet the electrical demand of the building and the ICE cogeneration system was used partially in the heating months of January, February and December and to a lesser extent in March and November to meet part of the electrical demand. This was because of the higher thermal demand in those months and therefore the cogenerated heat from the ICE system was used to meet part of the thermal demand, the remaining thermal demand was supplied by the gas boiler. In the average days of April through October, the thermal demand was supplied entirely by the gas boiler. The cooling demand was supplied primarily by the electric chillers in the 12 average days in the months. Figures 5-132, 5-133 and 5-134 show the percent power, heating and cooling supplied in the 12 days in the 12 months.

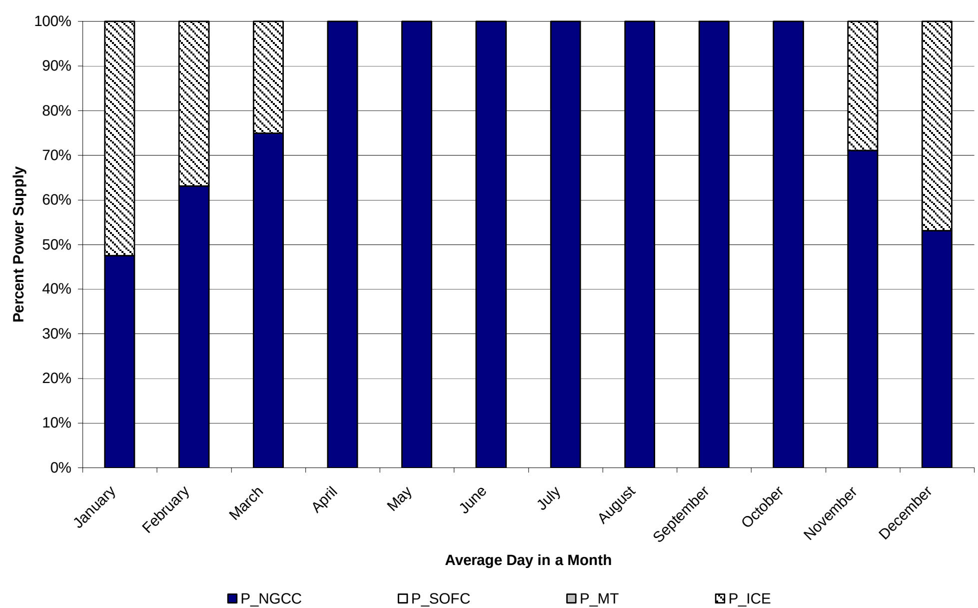



**Figure 5-132: Percent power supply from energy systems: Hourly Model for min cost (NGCC).**

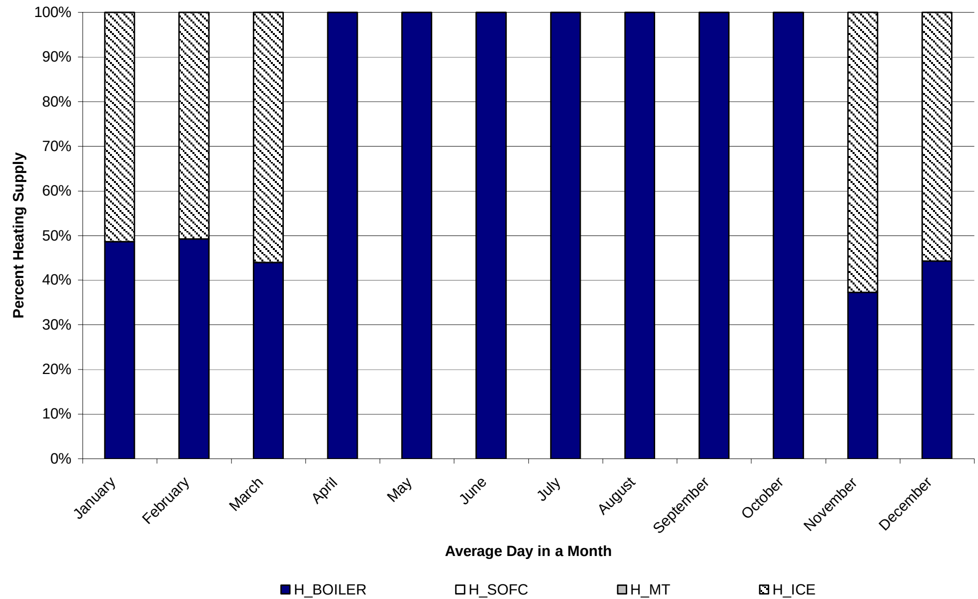



**Figure 5-133: Percent heating supply from energy systems: Hourly Model for min cost (NGCC).**

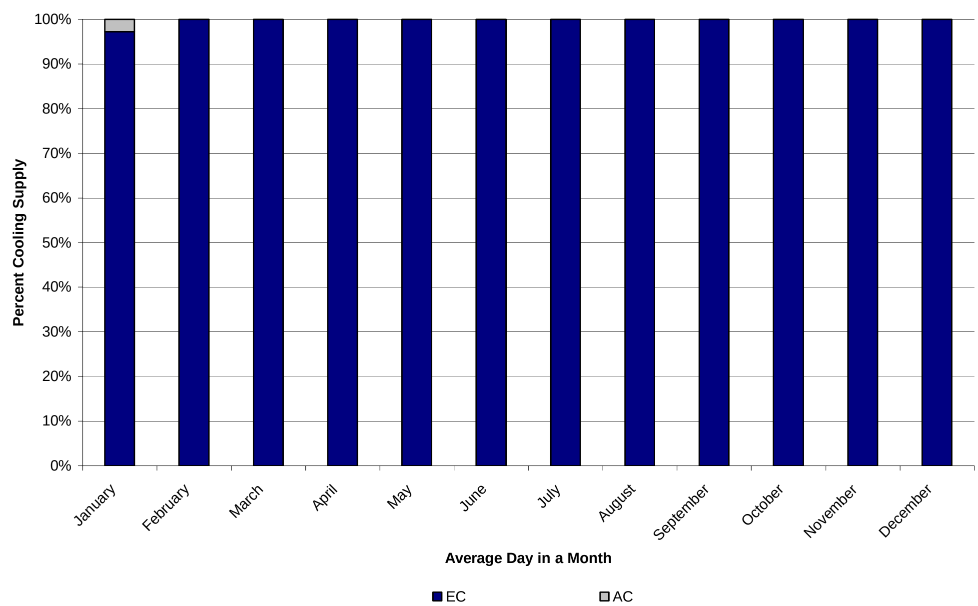



**Figure 5-134: Percent cooling supply from energy systems: Hourly Model for min cost (NGCC).**

When using the Simplified LCA Optimization Model to minimize cost in the year, the results obtained were similar to those obtained from the *Hourly LCA Optimization Model.* Figures 5-135 and 5-136 show the power supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified LCA Optimization Model* for minimizing cost, respectively. Figures 5-137 and 5-138 show the thermal energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified LCA Optimization Model* for minimizing cost, respectively. Figures 5-139 and 5-140 show the cooling energy supply and demand curves obtained from the results of the *Hourly LCA Optimization Model* and *Simplified LCA Optimization Model* for minimizing cost, respectively. The graphs indicate the similarity in operational trends of the building.

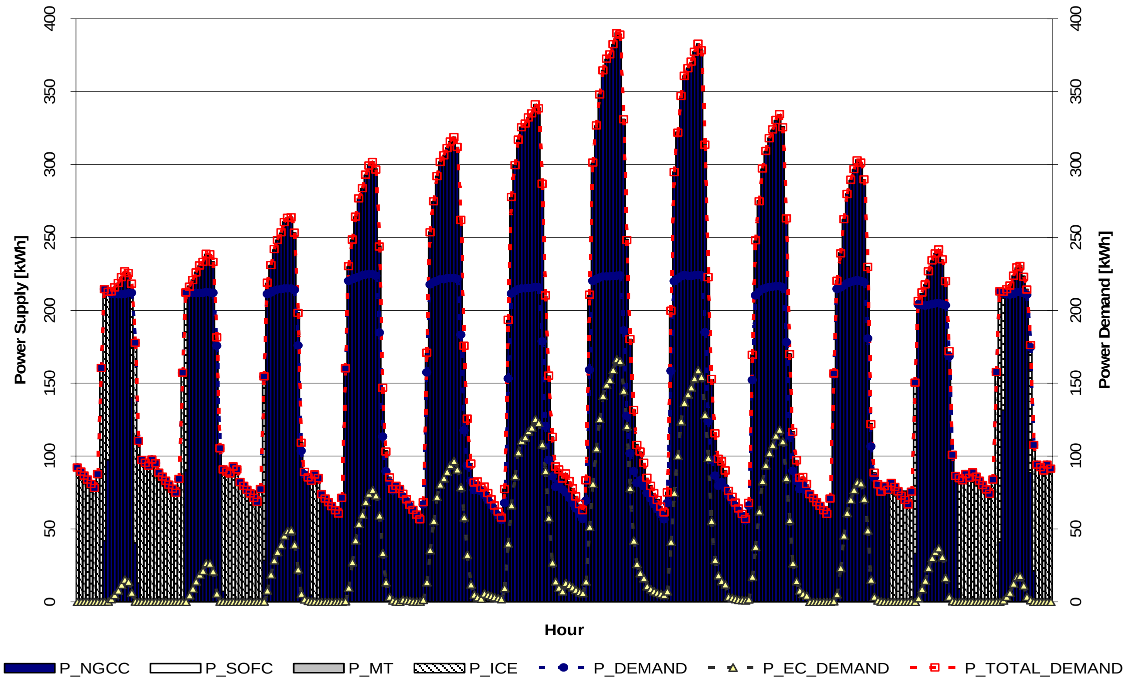



**Figure 5-135: Power supply: solution from Hourly Model (NGCC) for min cost.**

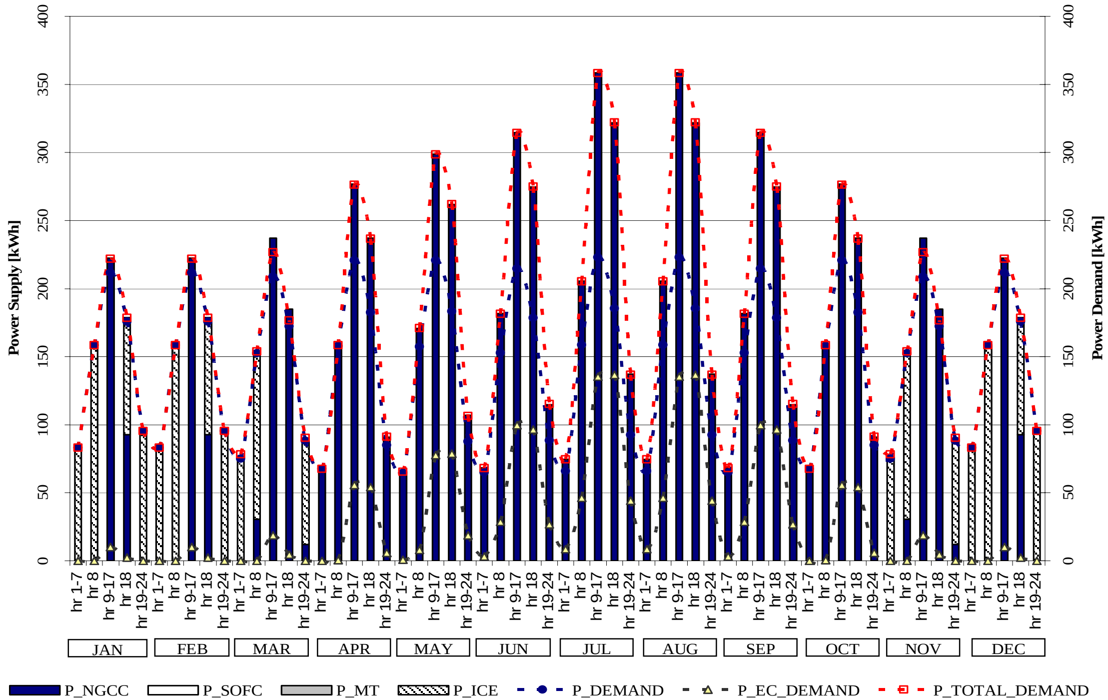



**Figure 5-136: Power supply: solution from Yearly Model (NGCC) for min cost.**

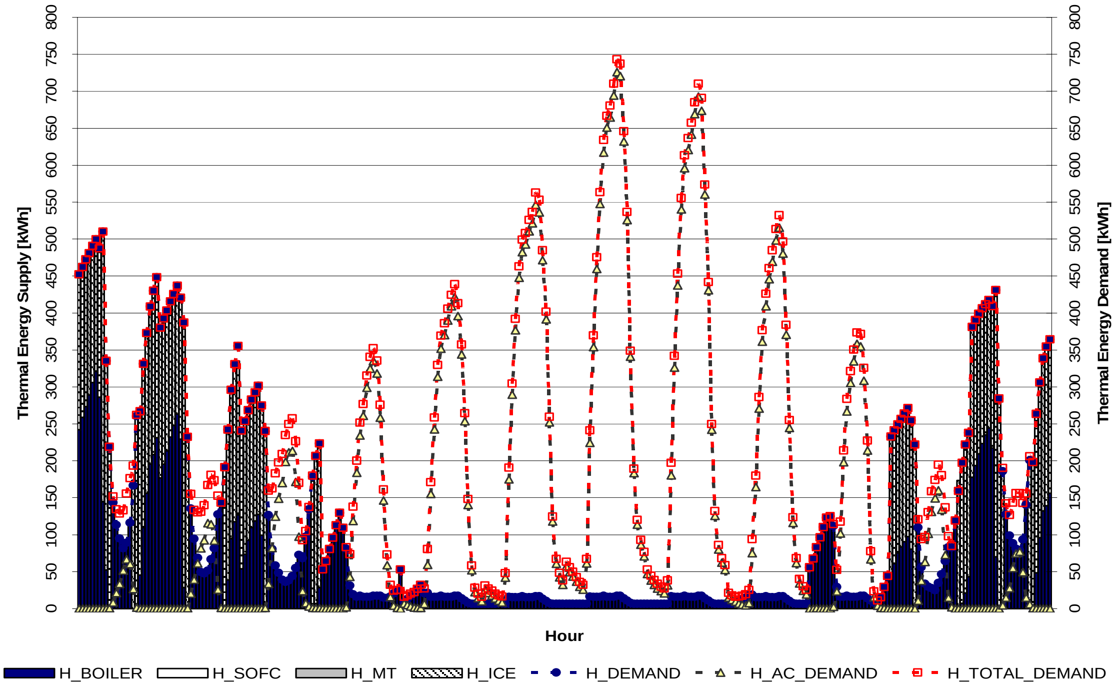



**Figure 5-137: Heating supply: solution from Hourly Model (NGCC) for min cost.**

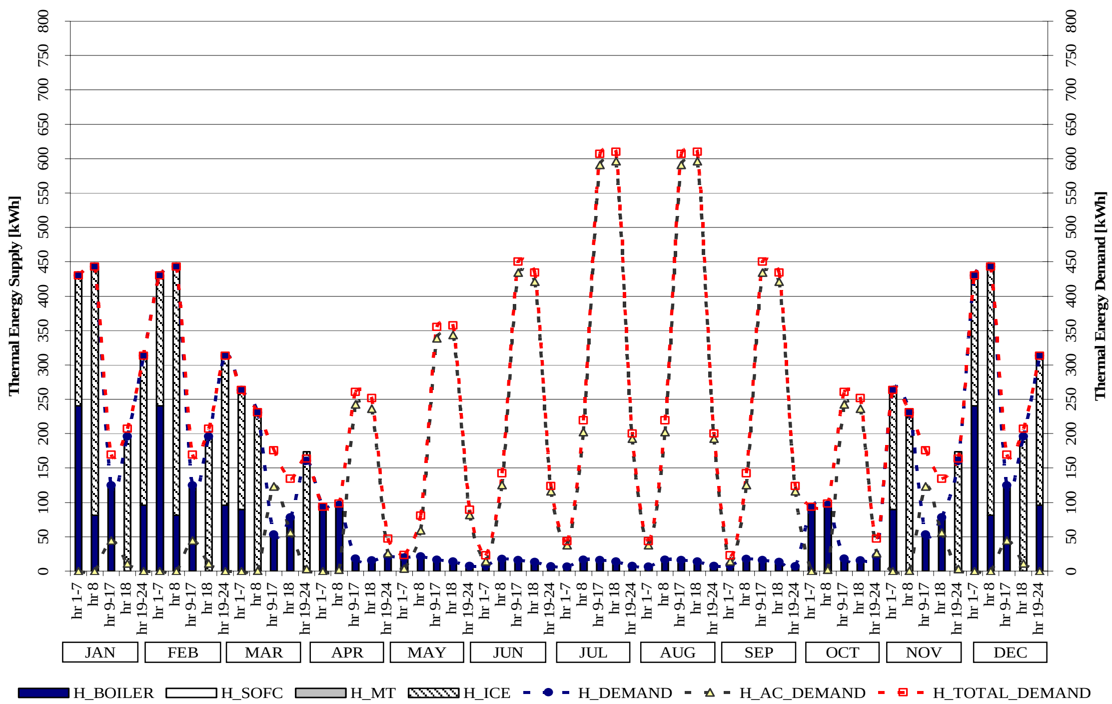



**Figure 5-138: Heating supply: solution from Yearly Model (NGCC) for min cost.**

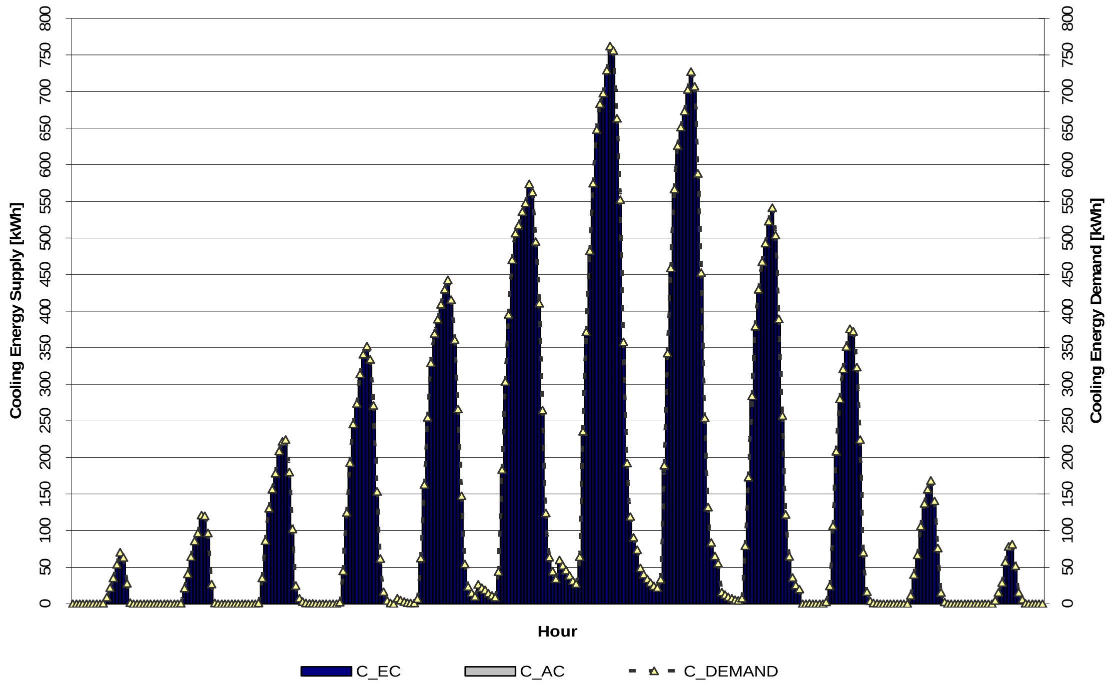



**Figure 5-139: Cooling supply: solution from Hourly Model (NGCC) for min cost.**

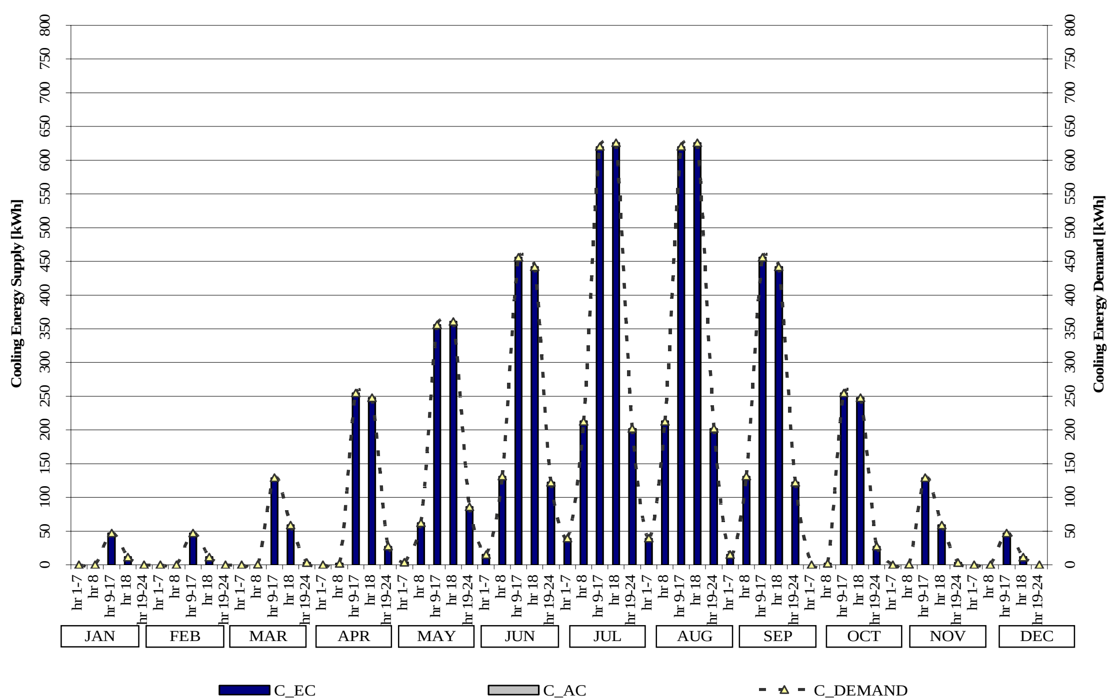



**Figure 5-140: Cooling supply: solution from Yearly Model (NGCC) for min cost.**

When the *Hourly LCA Optimization Model* to minimize cost, the trend in the objective values throughout the 12 days was similar to that exhibited by the other indicators: the value of the objective function was highest in the average day in January and decreased to low values in April and May and then increased again in June and July and decreased from July to the low values in September and October (lowest value) and increased in November to a high value in December, as shown in Figure 5-140. The values of the objective function and the corresponding indicator values are shown in Table 5-23. The increase in cost indicator values in the heating months (January, February and December) was due in part to the use of the ICE cogeneration system to supply part of the electrical demand; the remaining of the power demand was supplied by the NGCC power plant. The cost factor for the ICE cogeneration was relatively higher than the cost factor of the NGCC, an average of $0.128 and $0.068 per kWh, respectively.

The results obtained from the *Simplified Yearly LCA Optimization Model*, generated the total values of the objective function and the corresponding values of the other indicators. Figure 5-141 shows the values of cost in *$* corresponding to each objective function obtained from the *Simplified Yearly LCA Optimization Model* results. When minimizing the cost, PE, GWP, $CO_2$, and $SO_2$, the values of cost obtained were approximately in the same range, but the values of the cost increased by about 80% when minimizing TOPP, AP and $NO_x$ reflecting the higher cost of meeting the electrical demand using the combination of SOFC and MT cogeneration system, which were the systems used when minimizing TOPP, AP and $NO_x$, versus the NGCC and ICE cogeneration systems.

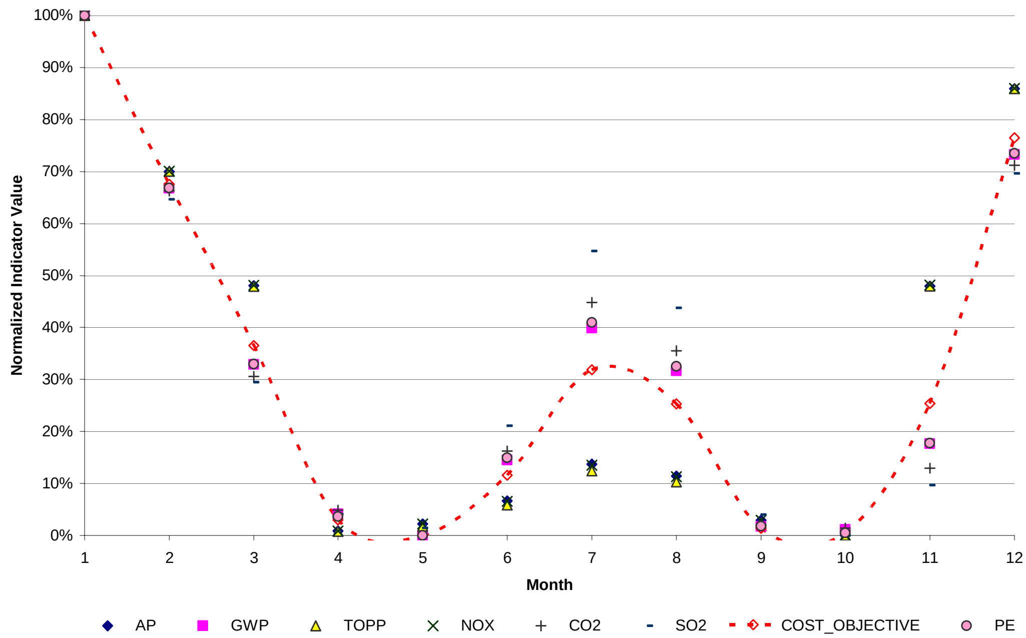
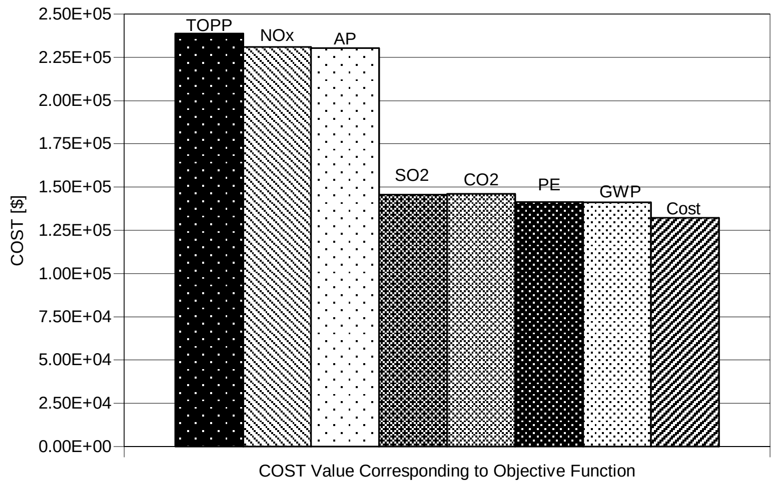



**Figure 5-141: Normalized indicator values corresponding to cost objective function (Hourly Model-NGCC).**

**Table 5-23: Indicator values corresponding to cost objective function (Hourly Model-NGCC).**

| | **AP** | **GWP** | **TOPP** | **PE** | **$NO_x$** | **$CO_2$** | **$SO_2$** | **COST Objective** |
|---|---|---|---|---|---|---|---|---|
| January | 5.12E+00 | 2.99E+03 | 1.01E+01 | 1.51E+04 | 7.27E+00 | 2.79E+03 | 6.34E-02 | 4.97E+02 |
| February | 4.10E+00 | 2.65E+03 | 8.01E+00 | 1.34E+04 | 5.80E+00 | 2.49E+03 | 5.70E-02 | 4.33E+02 |
| March | 3.35E+00 | 2.30E+03 | 6.49E+00 | 1.17E+04 | 4.73E+00 | 2.18E+03 | 5.06E-02 | 3.72E+02 |
| April | 1.73E+00 | 2.01E+03 | 3.25E+00 | 1.02E+04 | 2.43E+00 | 1.95E+03 | 4.60E-02 | 3.05E+02 |
| May | 1.78E+00 | 1.96E+03 | 3.32E+00 | 9.99E+03 | 2.49E+00 | 1.90E+03 | 4.55E-02 | 3.00E+02 |
| June | 1.93E+00 | 2.11E+03 | 3.60E+00 | 1.08E+04 | 2.70E+00 | 2.05E+03 | 4.91E-02 | 3.22E+02 |
| July | 2.18E+00 | 2.37E+03 | 4.05E+00 | 1.21E+04 | 3.04E+00 | 2.30E+03 | 5.52E-02 | 3.62E+02 |
| August | 2.10E+00 | 2.29E+03 | 3.90E+00 | 1.17E+04 | 2.93E+00 | 2.22E+03 | 5.32E-02 | 3.49E+02 |
| September | 1.81E+00 | 1.98E+03 | 3.36E+00 | 1.01E+04 | 2.53E+00 | 1.92E+03 | 4.60E-02 | 3.02E+02 |
| October | 1.70E+00 | 1.97E+03 | 3.19E+00 | 1.00E+04 | 2.38E+00 | 1.92E+03 | 4.52E-02 | 3.01E+02 |
| November | 3.34E+00 | 2.14E+03 | 6.49E+00 | 1.09E+04 | 4.74E+00 | 2.02E+03 | 4.70E-02 | 3.50E+02 |
| December | 4.64E+00 | 2.72E+03 | 9.10E+00 | 1.38E+04 | 6.58E+00 | 2.54E+03 | 5.79E-02 | 4.50E+02 |
| Lowest Value | 1.70E+00 | 1.96E+03 | 3.19E+00 | 9.99E+03 | 2.38E+00 | 1.90E+03 | 4.52E-02 | 3.00E+02 |
| Highest Value | 5.12E+00 | 2.99E+03 | 1.01E+01 | 1.51E+04 | 7.27E+00 | 2.79E+03 | 6.34E-02 | 4.97E+02 |




| | *COST Value Corresponding to Objective Function* |
|---|---|
| *TOPP Objective Function* | *2.39E+05* |
| *NOx Objective Function* | *2.31E+05* |
| *AP Objective Function* | *2.30E+05* |
| *SO2 Objective Function* | *1.46E+05* |
| *CO2 Objective Function* | *1.46E+05* |
| *PE Objective Function* | *1.41E+05* |
| *GWP Objective Function* | *1.41E+05* |
| *Cost Objective Function* | *1.32E+05* |

**Figure 5-142: Indicator values corresponding to cost objective function (Yearly Model-NGCC).**

#### 5.3.2.6 Pareto Optimal Solutions for Environmental Indicators & Cost

When analyzing the results obtained from the *Simplified LCA Optimization Model* for minimizing GWP and cost objective functions, the minimum GWP objective function value was 821,000 kg of $CO_2$ equivalents and the cost required to achieve that value was 141,000 \$. The minimum cost objective function value was 132,000 \$ and the GWP value obtained at that cost was 838,000 kg of $CO_2$ equivalents. Thus, 6% in cost reduction can be achieved when minimizing cost with respect to the maximum value of cost when reducing GWP. Only 2% in GWP reduction can be obtained when minimizing GWP, relative to the maximum value of GWP when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing GWP, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing GWP at fixed cost values. Figure 5-143 shows the Pareto optimal frontier derived for the GWP and cost objective functions.

When minimizing cost, most of the power demand was supplied by the NGCC power plant throughout the year except when the thermal demand was high, as in the months of January, February, March, and November. In these months, part of the power demand was supplied by the ICE cogeneration systems. The gas boiler provided most of the heating demand throughout the year except in the heating months, and cooling was provided by the electric chillers throughout the year. When minimizing GWP, most of the power requirements were supplied by the NGCC power plant. The ICE cogeneration system supplied part of the power demand in all months and the MT cogeneration system supplied about 10% of the power demand in the heating months. The heating demand was met mainly by the cogenerated heat from the ICE cogeneration systems in the months of May through September, and partially by the MT and the gas boiler in the heating months. The cooling demand was met mainly by the electric chiller and partially by the absorption chillers. The proportion of cooling supplied by the absorption chiller increased in the months of March through November.

As shown in Figure 5-143, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 134,000 \$) indicates a sharp decrease in GWP values with almost no increase in cost and the second region (points that laid beyond the cost of 134,000 \$) indicates a gradual decrease in the GWP and cost values up to the minimum GWP value. The main difference between the two regions was due to the slight decrease in power supply from the NGCC as the ICE started to be in use in the first region while the gradual decrease in GWP values in the second region reflected the gradual increase in ICE cogeneration system use especially in cooling days. This caused a shift in heating supply from the gas boiler to the use of cogenerated heat from the ICE cogeneration system and also a shift from using electric chillers to absorption chillers to meet the cooling demand.

When inspecting the results of each day in the 12 months using the *Hourly LCA Optimization Model*, the results showed that overall there was not a significant reduction in GWP. Generally, the GWP was reduced by as little as 0.5% in the months of May through September; about 2% in the months of January, February, November and December; and about 3% in the months of March, April and October. This is because of the relatively high efficiency of the NGCC power generation resulting in comparative emission factors to the cogeneration systems. Figure 5-144 shows the Pareto optimal frontier derived for the GWP and cost objective functions obtained in the 12 average days in the 12 months.

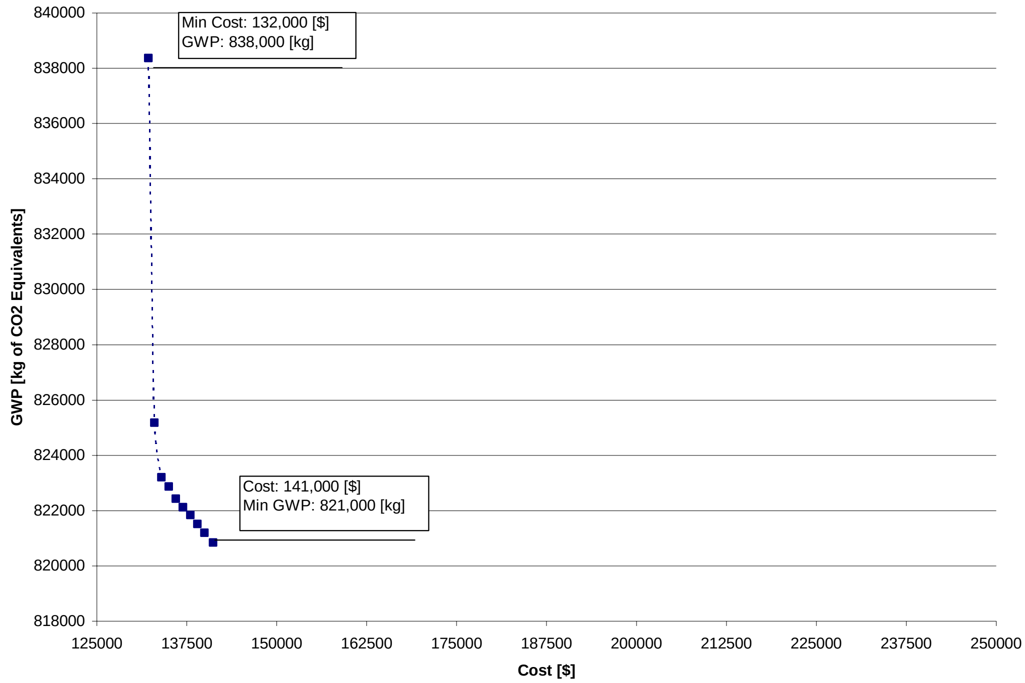



**Figure 5-143: Pareto optimal frontier for GWP and cost (Yearly Model-NGCC).**

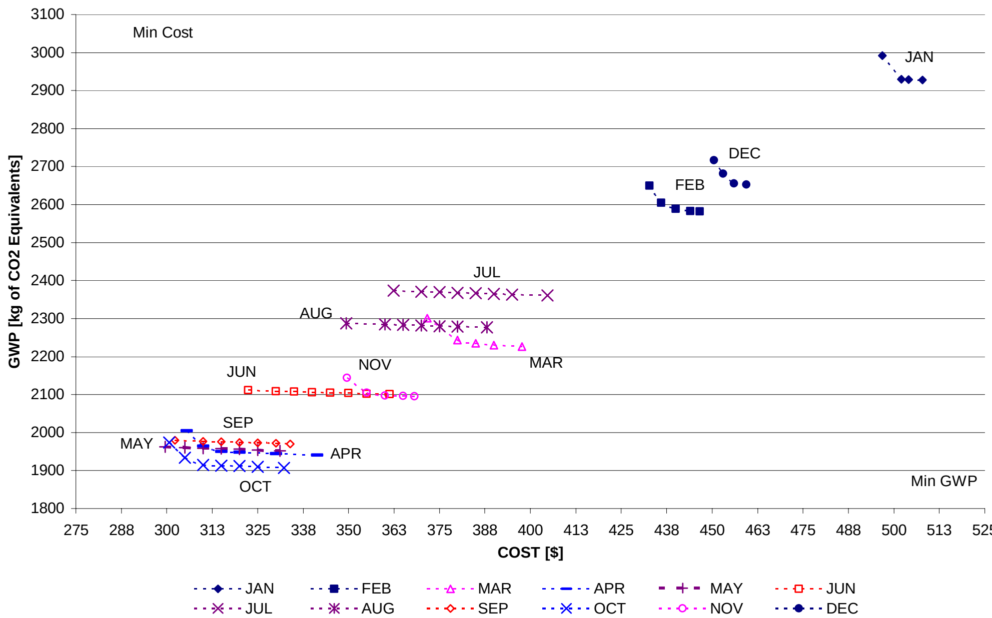



**Figure 5-144: Pareto optimal frontier for GWP and cost (Hourly Model-NGCC).**

When analyzing the results obtained from the *Simplified LCA Optimization Model* for minimizing $CO_2$ and cost objective functions, the minimum $CO_2$ objective function value was 753,000 kg and the cost required to achieve that value was 146,000 $. The minimum cost objective function value was 132,000 $ and the $CO_2$ value obtained at that cost was 801,000 kg. Thus, a 9% cost reduction relative to cost at minimum $CO_2$ can be achieved. A 6% reduction in $CO_2$ relative to $CO_2$ when minimizing cost can be attained. To investigate the tradeoffs between minimizing costs and minimizing $CO_2$, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing $CO_2$ at fixed cost values. Figure 5-145 shows the Pareto optimal frontier derived for the $CO_2$ and cost objective functions.

Since the results from minimizing $CO_2$ resembled the results obtained from minimizing GWP, the reasoning behind the reduction in emissions is similar. There was one main region in the graph (Figure 5-145) that reflected the reduction in $CO_2$ values with the shift of power supply from mainly the NGCC at minimum cost to a higher power supply proportion from the ICE cogeneration system (in addition to the NGCC) to meet the energy demand throughout the year rather than just partially during heating months as was the case when minimizing cost. Similarly, the heat supply was shifted from being met by the gas boiler to the cogeneration systems, except in the heating months where the gas boiler supplemented the heating supply. Also, the cooling supply shifted from being met by the electric chiller to the absorption chiller, while the electric chiller was used to meet part of the cooling demand when required in the cooling months.

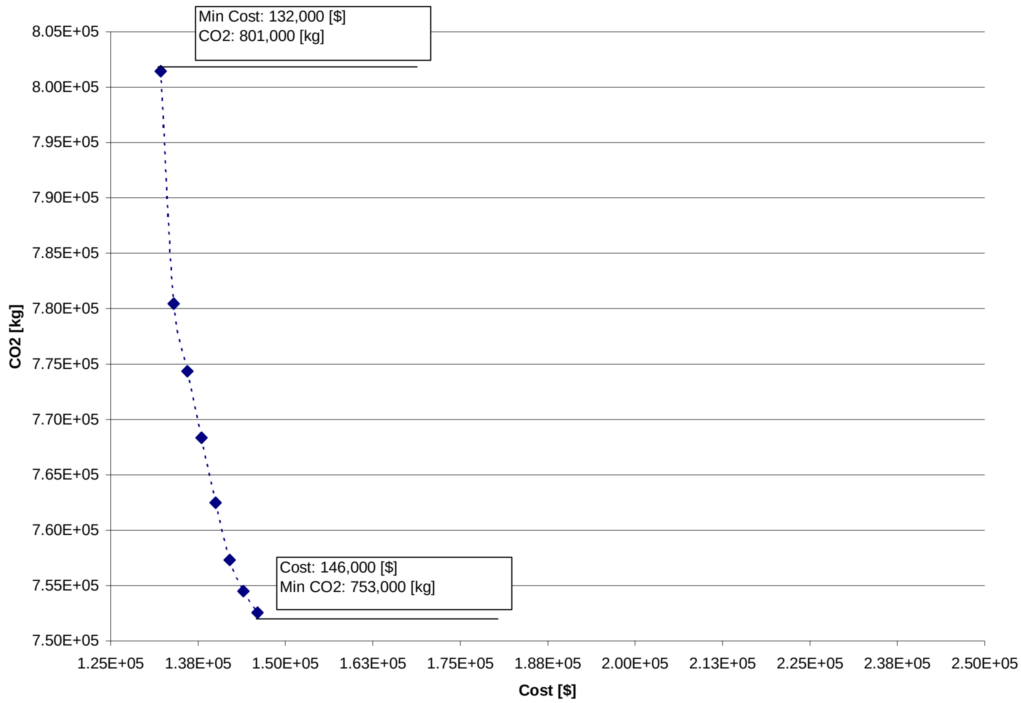



**Figure 5-145: Pareto optimal frontier for $CO_2$ and cost (Yearly Model-NGCC).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing TOPP and cost objective functions, the minimum TOPP objective function value was 395 kg of TOPP equivalents and the cost required to achieve that value was 239,000 $. The minimum cost objective function value was 132,000 $ and the TOPP value obtained at that cost was 194 kg of TOPP equivalents. Thus, a 45% cost reduction can be achieved when minimizing cost with respect to the maximum value of cost when minimizing TOPP. An 80% reduction in TOPP can be attained when minimizing TOPP relative to the maximum value of TOPP when minimizing cost. To investigate the tradeoffs between minimizing costs and minimizing TOPP, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing TOPP at fixed cost values. Figure 5-146 shows the Pareto optimal frontier derived for the TOPP and cost objective functions.

When minimizing TOPP with the NGCC, the results were similar to those obtained with problem set I, average electric grid: the power demand was supplied by the SOFC and MT cogeneration systems. Consequently, the heating demand was met by the cogenerated heat from the cogeneration systems. The cooling demand was met by the absorption chillers throughout the year except when the cooling demand was high when part of the cooling requirement was supplied by the electric chillers.

As shown in Figure 5-146, the graph is composed of two regions: the first region (points that laid between the minimum cost and the cost value of 140,000 $) indicates a sharp decrease in TOPP values as the cost values increased slightly and the second region (points that laid beyond the cost of 140,000 $) indicates the gradual decrease in the TOPP with the increase in cost values up to the minimum TOPP value. As the cost increased from 132,000 $ to 140,000 $, a 6% increase in cost, the TOPP decreased by 42% from 1940 kg of TOPP equivalents to 1130 kg of TOPP equivalents. The power supply shifted gradually from entirely NGCC power supply to partial supply by the MT cogeneration system while the NGCC contributed a high proportion of the power supply. This trend changed in the second region with the shift in power from the NGCC to an increase of the MT cogeneration system use with the gradual decrease in TOPP. At a 37% increase in cost relative to the minimum cost value, TOPP was reduced by 67%. At a 51% increase in cost relative to the minimum cost value (200,000 $), the SOFC was in use, resulting in a 75% reduction in TOPP. At 220,000 $, the energy demand was supplied completely by the SOFC and MT cogeneration systems and the NGCC was no longer in use.

The minimum value of TOPP was attained with an 81% increase in total cost relative to the minimum cost.

When inspecting the results of each day in the 12 months using the *Hourly LCA Optimization Model*, the results showed that an 84% (in heating months) to 75% (in cooling months) reduction in TOPP was attained in all days. The largest increase in cost to produce that reduction was during the heating months. Up to an 89% increase in cost occurred in January versus 71% in July relative to the minimum cost attained in those months, respectively. The higher reduction in TOPP obtained in the heating months was because the ICE cogeneration system was used to meet part of the energy demand in the months of January, February, March, November and December. The ICE was not used in the months of April through September when power was supplied by the NGCC and heat was supplied by the gas boiler. Since the TOPP emission factor for the ICE is higher than the TOPP emission factors for the NGCC, boiler, MT, and SOFC, the resultant TOPP values during the heating months were higher than those obtained during the months of April through September. Therefore, the reduction in TOPP values was higher in the heating months, because the minimum TOPP values in the 12 months are similar. Figure 5-147 shows the Pareto optimal frontier derived for the TOPP and cost objective functions obtained in the 12 average days in the 12 months.

The highest potential for reducing TOPP (up to 84% in January) occurred in the heating months. The power demand is initially met by the NGCC and ICE cogeneration system and gradually shifts to MT and SOFC cogeneration systems. Also, the heating demand is shifted from the gas boiler to the cogenerated heat. Finally, the use of electric chillers to meet the cooling demand is replaced by absorption chillers. That is achieved with an 89% increase in cost relative to the minimum cost.

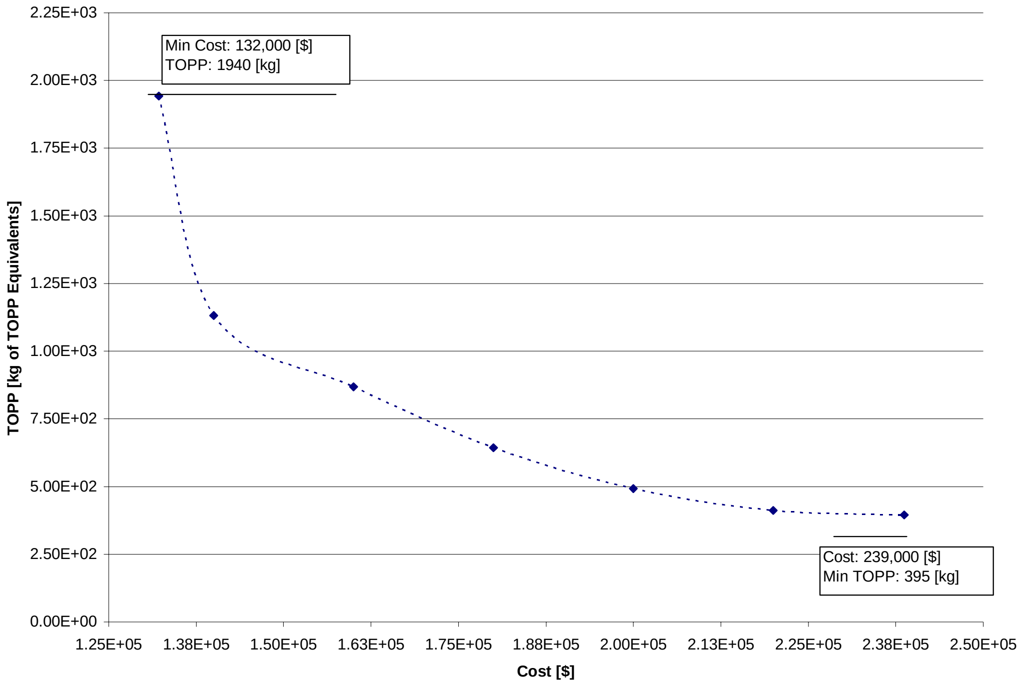



**Figure 5-146: Pareto optimal frontier for TOPP and cost (Yearly Model-NGCC).**

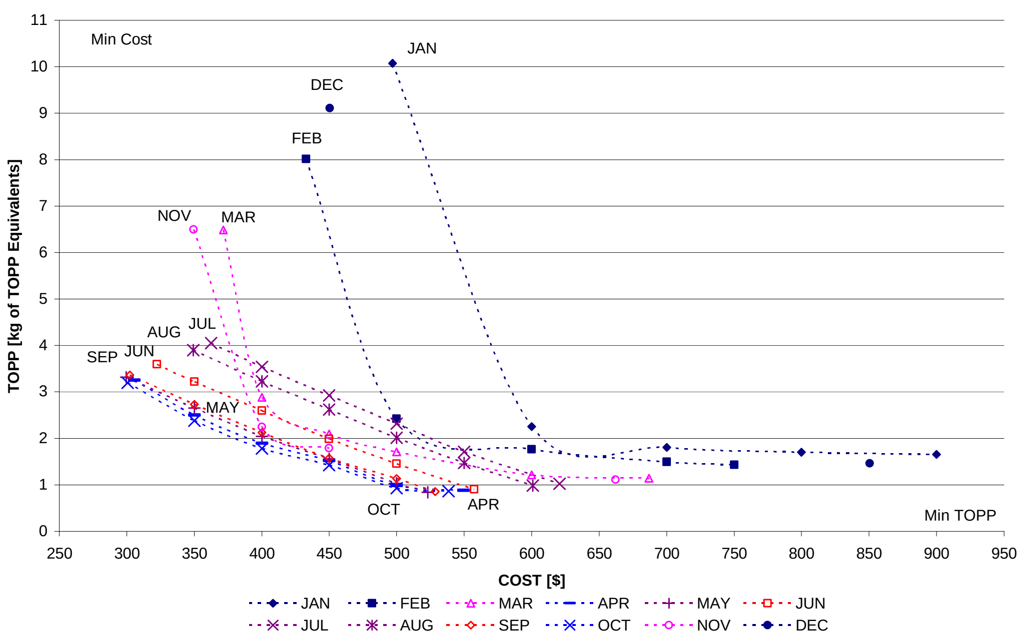



**Figure 5-147: Pareto optimal frontier for TOPP and cost (Hourly Model-NGCC).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing AP and cost objective functions, the minimum AP objective function value was 225 kg of $SO_2$ equivalents and the cost required to achieve that value was 230,000 $. The minimum cost objective function value was 132,000 $ and the AP value obtained at that cost was 1010 kg of $SO_2$ equivalents. A 43% reduction in cost with respect to maximum cost when minimizing AP can be achieved when minimizing cost. A 78% reduction relative to the maximum value of AP when minimizing cost can be attained when minimizing AP. To investigate the tradeoffs between minimizing costs and minimizing AP, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing AP at fixed cost values. Figure 5-148 shows the Pareto optimal frontier derived for the AP and cost objective functions.

The results obtained for minimizing AP was similar to those obtained when minimizing TOPP. There are two main regions in the graph (Figure 5-148) where in the first region (points that laid between the minimum cost and the cost value of 140,000 $), the decrease in AP values were sharp because of the shift of power supply from the NGCC to the cogeneration systems, whereas the second region (points that laid beyond the cost value of 140,000 $), the decrease in AP values was gradual with increasing cost as more of the energy demand was met by the SOFC and MT cogeneration systems. Consequently, the heating demand was met by the cogenerated heat. The cooling demand was met by the absorption chillers throughout the year except when the cooling demand was high when part of the cooling requirement was supplied by the electric chillers.

With a 6% increase in cost, AP decreased by 42% from 1010 kg of $SO_2$ equivalents to 591 kg of $SO_2$ equivalents. The power supply shifted gradually from the NGCC as the main power supply to power being partially supplied by the MT cogeneration system. The NGCC power plant continued to contribute a high proportion of the power supply. There was no supply from the ICE cogeneration system. AP continued to decrease as the MT supplied a higher proportion of the energy demand and the power supply from the NGCC decreased and the heating supply from the gas boiler decreased. At the cost of 200,000 $, a 51% increase in cost relative to the minimum cost value, the SOFC was in use in addition to the MT cogeneration system and the NGCC power plant, reducing the AP by 74% (268 kg of $SO_2$ equivalents) relative to the value of AP obtained at minimum cost. The AP value then stabilized and the minimum value of AP was obtained at 74% increase in total cost, relative to minimum cost.

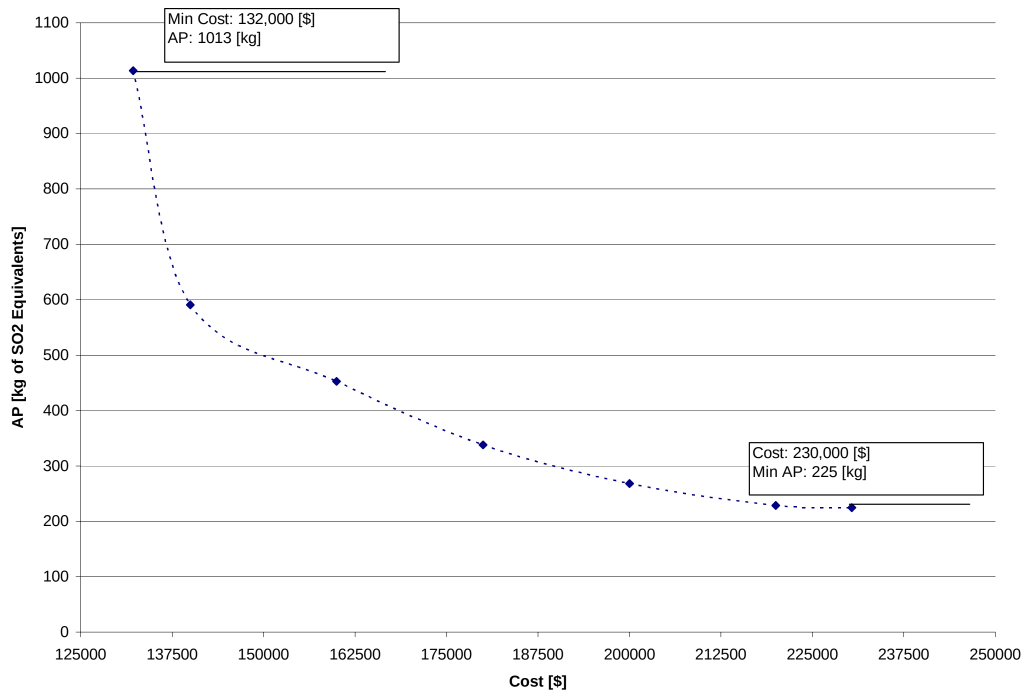



**Figure 5-148: Pareto optimal frontier for AP and cost (Yearly Model-NGCC).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing $NO_x$ and cost objective functions, the minimum $NO_x$ objective function value was 278 kg and the cost required to achieve that value was 231,000 $. The minimum cost objective function value was 132,000 $ and the $NO_x$ value obtained at that cost was 1430 kg. Thus, a 43% cost reduction relative to the maximum value of cost when minimizing NOx can be achieved when minimizing cost. An 81% $NO_x$ reduction with respect to the maximum value of NOx when minimizing cost can be attained when minimizing $NO_x$. To investigate the tradeoffs between minimizing costs and minimizing $NO_x$, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing $NO_x$ at fixed cost values.

Figure 5-149 shows the Pareto optimal frontier derived for the $NO_x$ and cost objective functions. The results generally resembled those obtained from the Pareto optimal solutions for minimum AP and cost. As shown in the Figure 5-149, there are two main regions in the graph: in the first region (points that laid between the minimum cost and the cost value of 140,000 $), the decrease in $NO_x$ values was sharp with minimal increase in cost: A 43% reduction in $NO_x$ was obtained by only a 6% increase in cost, relative to the minimum cost values, due to the shift in the power supply from the NGCC and ICE cogeneration system to partial supply of energy by the MT cogeneration system. The ICE cogeneration system was no longer in use at that point. In the second region of the graph (points that laid beyond the minimum cost value of 140,000 $), the decrease in $NO_x$ values was gradual with gradual increase in cost: the $NO_x$ continued to decrease and at the cost of 200,000 [$], the SOFC supplied part of the energy requirement, causing a total of 76% $NO_x$ reduction relative to the value obtained at minimum cost. $NO_x$ continued to be reduced as the SOFC supplied more of the energy requirement, supplemented by the MT while the power supply from the NGCC was reduced. It was no longer in use at minimum $NO_x$, where the total increase in cost was 75% relative to the minimum cost.

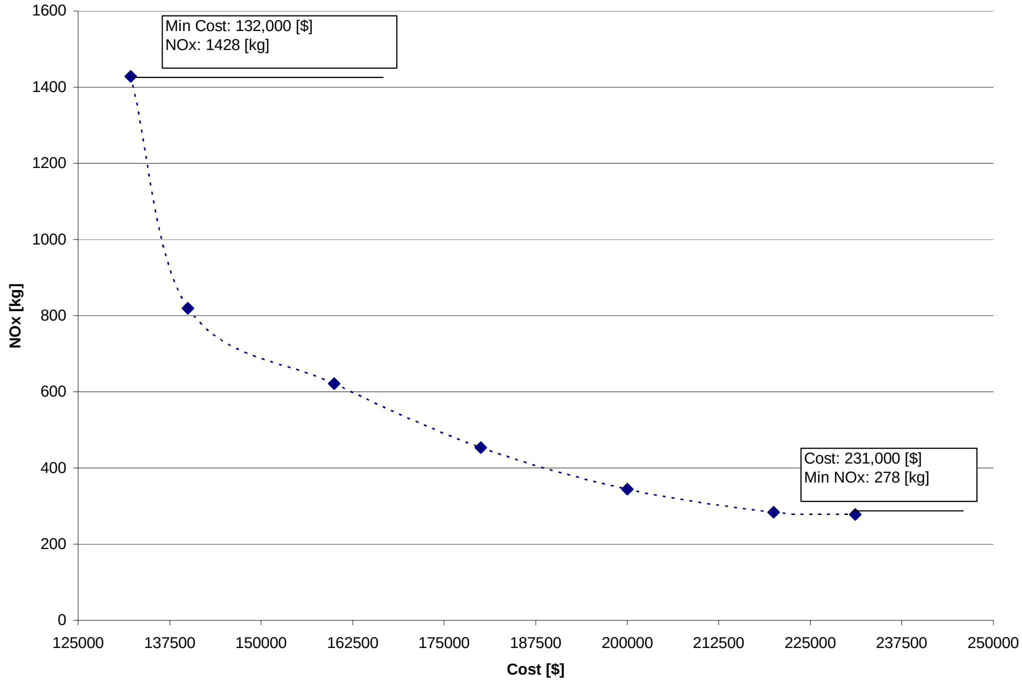



**Figure 5-149: Pareto optimal frontier for $NO_x$ and cost (Yearly Model-NGCC).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing $SO_2$ and cost objective functions, the minimum $SO_2$ objective function value was 18 kg and the cost required to achieve that value was 146,000 $; whereas, the minimum cost objective function value was 132,000 $ and the $SO_2$ value obtained at that cost was 19 kg. Thus, a 9% reduction in cost (with respect to the maximum value of cost when minimizing $SO_2$) can be achieved when minimizing cost. A 5% reduction in $SO_2$ relative to the maximum value of $SO_2$ can be obtained when minimizing $SO_2$. To investigate the tradeoffs between minimizing costs and minimizing $SO_2$, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing $SO_2$ at fixed cost values. Figure 5-150 shows the Pareto optimal frontier derived for the $SO_2$ and cost objective functions.

Similar to the results obtained from minimizing $CO_2$, the decrease in $SO_2$ from that obtained at minimum cost was due to shift of power supply from the NGCC to ICE cogeneration system to meet the energy demand throughout the year rather than just partially supplying energy during the heating months. Similarly, heat supply shifted from being met by the gas boiler to being supplied by the cogeneration systems except in the heating months where the gas boiler supplemented the heating supply. The cooling supply also shifted from being primarily met by the electric chiller to primarily being met by the absorption chiller. The electric chiller was used only to meet partial of the cooling demand when required in the cooling months.

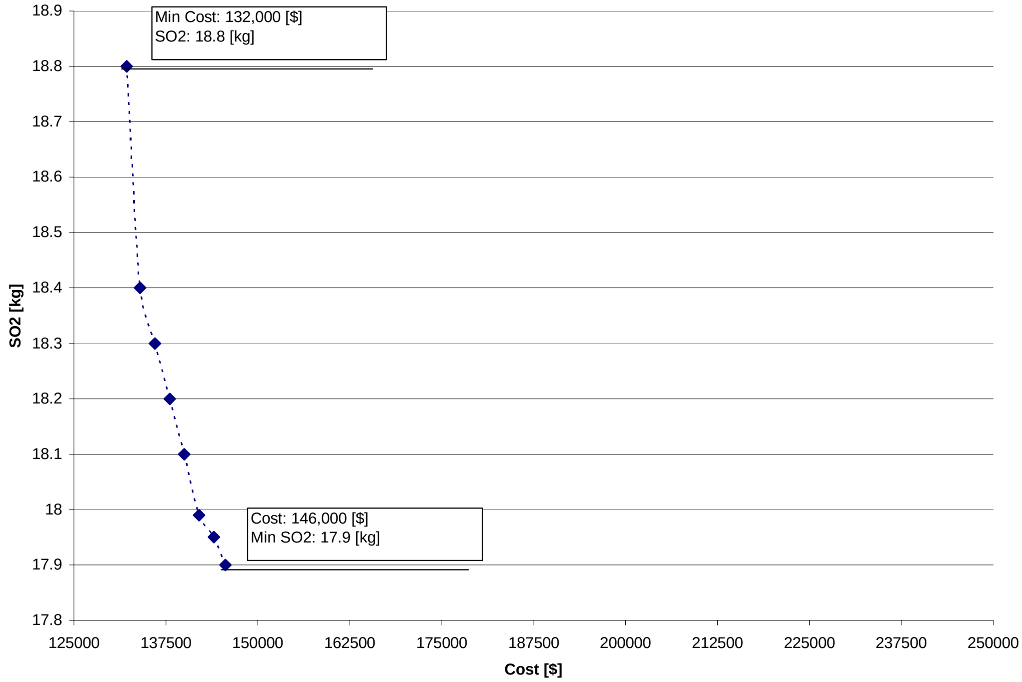



**Figure 5-150: Pareto optimal frontier for $SO_2$ and cost (Yearly Model-NGCC).**

When analyzing the results obtained from the *Simplified LCA Optimization Model*, for minimizing PE consumption and cost objective functions, the minimum PE objective function value was 4,180,000 kWh and the cost required to achieve that value was 141,000 $. The minimum cost objective function value was 132,000 $ and the PE value obtained at that cost was 4,260,000 kWh. A 6% cost reduction with respect to the maximum value of cost when minimizing PE can be achieved when minimizing cost. A 2% PE reduction relative to the maximum value of PE when minimizing cost can be obtained when minimizing PE. To investigate the tradeoffs between minimizing costs and minimizing PE, the *Simplified LCA Optimization Model* was used to find the Pareto optimal solutions between the two extreme points by minimizing PE at fixed cost values. Figure 5-151 shows the Pareto optimal frontier derived for the PE and cost objective functions.

As shown in Figure 5-151, there are two main regions in the graph: in the first region (points that laid between the minimum cost and the cost value of 134,000 $), the values of the PE decreased significantly with almost no increase in cost due to the introduction of MT use in addition to the increase in ICE use. In the second region (regions beyond 1340,000), the PE values decreased gradually with a slight increase in cost due to the gradual increase in the use of MT and ICE cogeneration systems to supply part of the energy demand in addition to the NGCC power plant. The use of only the NGCC power plant and gas boiler to supply the power and heating demand in the months from April through September when minimizing cost shifted to meeting part of the power and heating demand with the ICE cogeneration systems in those months resulted in a slight decrease in PE and a slight increase in cost.

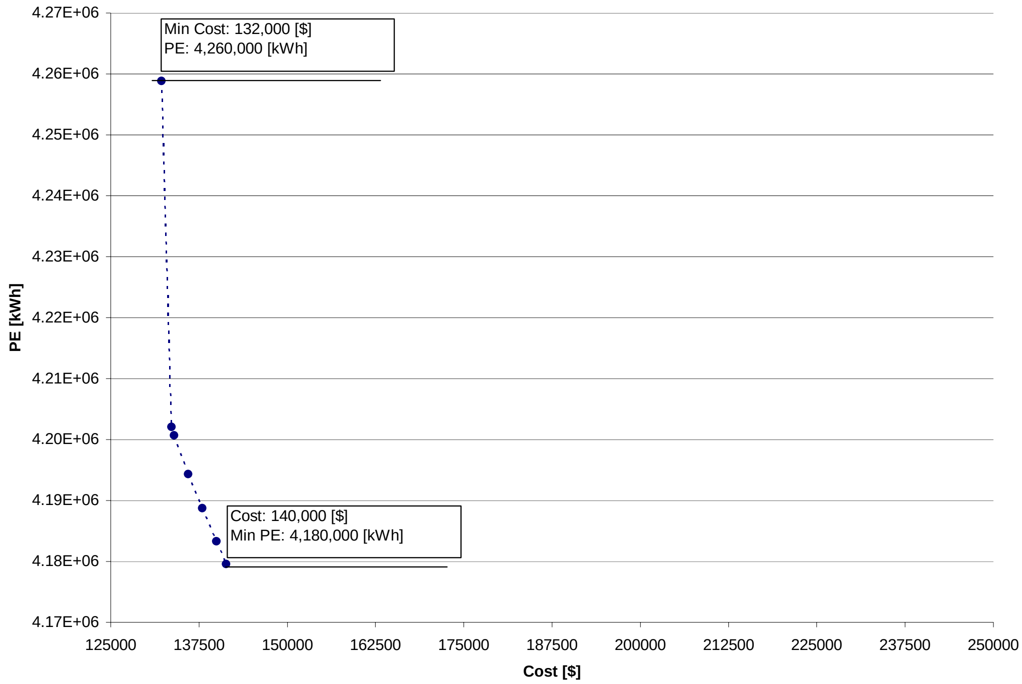



**Figure 5-151: Pareto optimal frontier for PE and cost (Yearly Model-NGCC).**

The results obtained from the Pareto optimal solutions for the environmental indicators and cost indicated that nominal decreases in GWP, $CO_2$, $SO_2$ and PE indicator values relative to the values obtained at minimum cost were obtained with relatively low increments in cost due to the shift of energy use from the NGCC as the main power source when minimizing cost to cogeneration systems when minimizing the environmental indicators. Figure 5-151 show the Pareto optimal frontier derived for the normalized environmental and cost objective functions.

A 6% decrease in $CO_2$ value relative to the $CO_2$ value obtained at minimum cost was obtained with only an 11% increase in cost, relative to the minimum cost value. Likewise, only a 2% decrease in GWP value was obtained with a 7% increase in cost; a 5% decrease in $SO_2$ value was obtained with 10% increase in cost, and a 2% decrease in PE value with a 7% increase in cost. Hence, there was no overall significant decrease in GWP, $CO_2$, $SO_2$ and PE values relative to the values obtained at minimum cost when using cogeneration systems to replace the NGCC power supply. This is because the GWP, $CO_2$, $SO_2$, and PE emission factors of the NGCC approach those of the cogeneration systems.

On the other hand, there was a significant decrease in TOPP, AP and $NO_x$ indicator values relative to the values obtained at minimum cost. This resulted in a large increment in cost, reflecting the shift in use from the NGCC to the MT and the SOFC cogeneration systems. An approximately 78% decrease in AP, a 80% decrease in TOPP and a 81% decrease in AP indicator values (relative to the values obtained at minimum cost) were attainable with a 74%, 81% and 75% increase in cost relative to the minimum cost values, respectively.

The difference in the trends between the first group of indicators: GWP, PE, $CO_2$ and $SO_2$, and the second group of indicators: TOPP, AP and $NO_x$ was mainly because: first, the cost difference between the NGCC (which was the main source for power supply when minimizing cost) and the cost of using cogeneration systems, when minimizing the first group of indicators, was low leading to a decrease in the values of the indicators with a minimal increase in cost; and second, because the values of the indicator factors associated with the NGCC approached those associated with the cogeneration systems (used when minimizing the indicator values), there was no significant decrease in the values of the indicators from those obtained at minimum cost. However, with the second group of indicators (TOPP, AP and $NO_x$) the decrease in indicator values was gradual with higher increment in cost values mainly because the difference in cost between the NGCC and the SOFC and MT cogeneration systems was high.

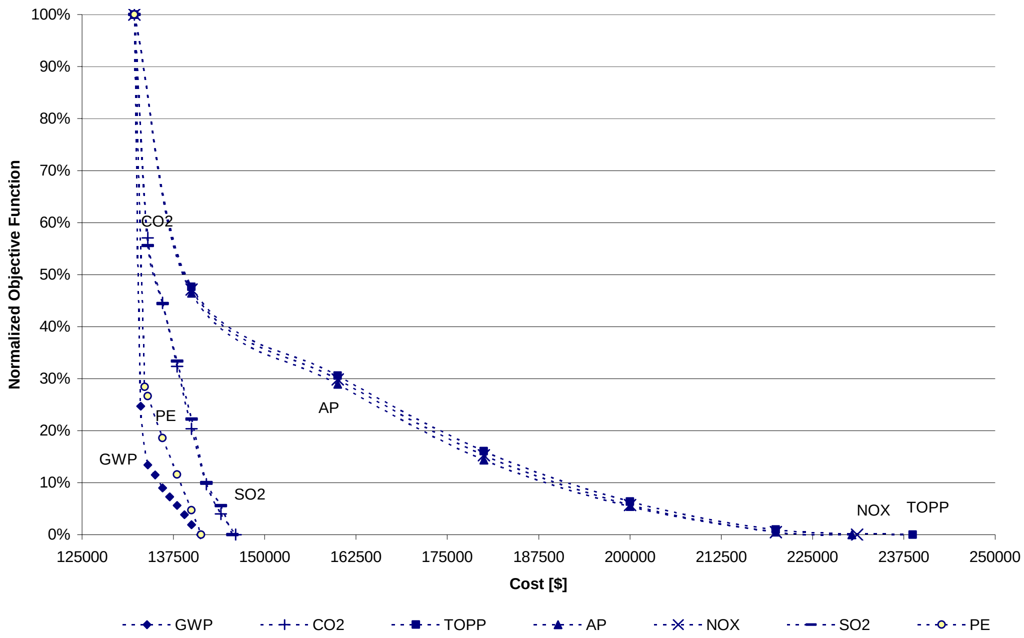



**Figure 5-152: Pareto optimal frontier for the normalized environmental and cost (Yearly Model-NGCC).**

## 6.0 CONCLUSION AND CONTRIBUTIONS

The dissertation focuses on optimizing the operation of commercial office buildings by considering the potential life cycle environmental impacts that might result from meeting the energy demand of a building. With the exception of a few studies that addressed reducing carbon dioxide emission rates or energy usage rates (Burer *et al.*, 2003; Wu and Rosen, 1999; and Chung *et al.*, 1997), the majority of previous work has focused on the optimization of the operation of a utility plant by minimizing cost and maximizing revenues (Kamimura *et al.*, 1999, Benelmir and Feidt, 1998; Marechal and Kalitventzeff, 1998; Arivalagan *et al.*, 1995; and Venkatesh and Chankong, 1995). Several studies addressed the effects of process parameters on improving the efficiency and reducing the cost of generating electricity from cogeneration systems (Yilmaz, 2004; Pangalis et al., 2002; and Riensche *et al.*, 1998). A gap exists in the established literature in assessing the cumulative life cycle environmental impacts that might result from building operation. The combination of life cycle environmental impact assessment, hourly building energy use data, and operations research techniques presents an alternative approach to evaluating building energy systems.

### 6.1 RESULTS SUMMARY & INTERPRETATION

The optimization model implemented on the hypothetical case study was used to examine the operational performance of a typical office building operation. Based on simulated hourly energy use data, the *Hourly LCA Optimization Model* and the *Simplified Yearly LCA Optimization* model were implemented to optimize the performance of the office building hourly operation for 12 average days of the months (evaluated individually) and the hourly operation for the whole year, respectively. Two problem sets for each optimization model were formulated to consider two utility alternatives: electricity from the average electric grid and the more efficient NGCC central power plant. The following objective functions were evaluated for each of the problem sets:

(a) Minimizing the potential life cycle emissions for each of the following indicators: GWP, AP, TOPP, $CO_2$, $SO_2$ and $NO_x$;
(b) Minimizing the potential life cycle primary energy (PE) consumption; and
(c) Minimizing cost.

Generally, for all the objective functions, the results obtained from the *Simplified Yearly LCA Optimization Model* resembled those obtained from the *Hourly LCA Optimization Model* results. The solution of the *Hourly LCA Optimization Model* problems generated the values of the objective function and the optimum hourly operational strategy of an energy system(s) for each individual day. On the other hand, the solution of the *Simplified Yearly LCA Optimization Model* problems generated the values of the objective function and the hourly operational strategy of an energy system(s) for the whole year based on aggregated energy use data. In other words, the results from the *Simplified Yearly LCA Optimization Model* could be interpreted as an approximation of the operation of energy systems during the year based on representative energy usage data for the year. Unlike the results from the *Simplified Optimization Model*, which generated the value of the objective function for the whole year, the solution of the *Hourly LCA Optimization Model* problems generated the minimum values of the objective function for each day in the year. This information could be used to predict when the best building performance occurs during the year based on the minimum value of the objective function.

### 6.1.1 Problem Set (I) for Average Electric Grid Utility Option

When the *Hourly LCA Optimization Model*[12] was used to minimize the potential life cycle GWP and $CO_2$ indicators that might result from meeting the office building's energy demand in the 12 days in the months of January through December, the results indicated that it was optimum to use the ICE cogeneration system to provide more than 50% of the power and thermal demand of the building. Generally, the MT cogeneration system was used to meet part of the energy

[12] The *Simplified Yearly Optimization Model* gave similar results to the hourly model.

demand, and the average electric grid was used to provide less than 10% of the power demand. The electric grid was used primarily when the cooling demand increased and the heating demand decreased, i.e., during the months of April through November. The gas boiler was used to supply less than 30% of the heating demand. The boiler was used when the thermal demand was relatively high, as in the months of January, February, March, November and December. The absorption chiller was used to meet most of the cooling demand, while the electric chiller was only used during the cooling months to supply part of the demand. Because the heat produced from the cogeneration systems was utilized to meet most of the heating and cooling demand, the combination of the ICE and MT cogeneration system were chosen over the average electric grid and the gas boiler, resulting in lower GWP and $CO_2$ values.

Overall, the results obtained from the $SO_2$ minimization problem were similar to the GWP and $CO_2$ results with the exception that there was no power supply from the grid on any of the days, i.e., the ICE and MT cogeneration systems were used to meet the energy demand of the building in the 12 typical days in the months of January through December. In addition, because of the relatively higher $SO_2$ emission factors of the MT cogeneration system compared to the ICE cogeneration system, the proportion of energy supplied from the MT was lower than when minimizing GWP and $CO_2$.

When using the *Hourly LCA Optimization Model* in the TOPP, AP and $NO_x$ minimization problems, the results indicated that it was optimum to use the SOFC and MT cogeneration systems to meet the power, heating and cooling demands of the building. Generally, the SOFC provided more than 40% of the power demand and its use decreased during the heating months, when the MT cogeneration systems supplied a higher proportion of the power demand. This is because the SOFC has a higher power to heat ratio than the MT cogeneration system, and therefore was more efficient for use in the cooling months to supply the cooling demand with electric chillers. The higher thermal efficiency ratio of the MT cogeneration system was more suitable in the heating months in order to meet the heating demand of the building.

The results obtained from *Hourly LCA Optimization Model* for the PE minimization problem indicated that it was optimum to supply more than 70% of the power demand with electricity from the ICE cogeneration system and the remainder from the average electric grid during the heating months. As the cooling demand increased and the heating demand decreased in the months of April through October, it was optimum to use the SOFC to supply more than

55% of the power demand and the ICE cogeneration system to meet the remainder of the power demand. This was due to the relatively higher power to heat ratio of the SOFC compared to the ICE cogeneration system. The power was primarily used by the electric chillers to meet the cooling demand, whereas the higher thermal efficiency ratio of the ICE was efficient in meeting most of the heating demand in the heating months.

The results obtained from the *Simplified Yearly LCA Optimization Model* for the PE minimization problem, on the other hand, showed a different trend in the energy system use in the heating months. This model indicated it was optimum to use the SOFC in addition to the ICE cogeneration system instead of the average electric grid as indicated in the *Hourly LCA Optimization Model* results. This is mainly due to the aggregation in energy use data used in *Simplified Yearly LCA Optimization Model.* When inspecting the Pareto optimal solutions for the PE and cost using the *Simplified Yearly LCA Optimization Model*, it was found that there were no significant differences in the values of PE obtained at close to minimum PE. For example, a 0.9% decrease in PE (from 4,506,060 to 4,461,200 kWh) resulted in a cost increase of 7% (from $180,000 to $191,000). However, at minimum PE (4,461,200 kWh ), the SOFC was in use whereas in the previous point (4,506,060 kWh) the SOFC was not in use and the average electric grid and ICE cogeneration systems were in use. Therefore, the approximation in data in the *Simplified Yearly LCA Optimization Model* resulted in different results than those obtained with the *Hourly LCA Optimization Model*.

The analysis of the results showed that the cogeneration systems followed the electric load of the building with no excess cogenerated heat in the heating months. If required, the gas boiler provided supplemental heat. As the cooling demand increased, the cogeneration systems continued to follow the electric load of the building and increased their power output, which resulted in the production of heat greater than the heating demand, and therefore produced excess heat. The cogeneration systems were ideal in meeting the energy demand of the building with high electric savings in the cooling months, where the power demand was met before reaching the peak power requirement. This was mainly because the cogenerated heat was used to meet the cooling demand with an absorption chiller, in addition to the partial use of the electric chiller. On the other hand, when minimizing cost, the optimum was found to be meeting the power demand with the average electric grid in all the months except the heating months. In the heating months, part of the power demand was supplied by the ICE cogeneration system. The min cost results showed that the energy systems reached the total peak electric demand throughout the year in order to meet the power and cooling requirement of the building and no cogeneration systems were in use in the cooling months.

Generally, in the climate and building type used in the case study, the highest values of the environmental indicator objective functions occurred in the heating months of January, February and December. In these months, supplemental heat, i.e., the gas boiler, was used to meet the heating demand. There was no advantage to running the cogeneration systems above the electrical demand. In the remainder of the months, the objective function values decreased as the cogeneration systems were able to meet most of the electrical as well as thermal demand without using the gas boiler; however, a slight increase in the objective function values occurred in the cooling months due to the increase in energy generation to meet the high cooling demand.

The results from the *Simplified Yearly LCA Optimization Model* indicated that approximately equal GWP values were obtained when minimizing the GWP, $CO_2$ and $SO_2$ objective functions. However, the GWP values increased by 30%-37% when minimizing PE and cost, respectively, and approximately up to 50% when minimizing TOPP, AP and $NO_x$. Similarly, approximately equal $CO_2$ values were obtained when minimizing GWP, $CO_2$ and $SO_2$ objective functions and the $CO_2$ values increased by approximately 40% when minimizing PE and cost, and approximately up to 66% when minimizing TOPP, AP, and $NO_x$.

The values of $SO_2$ obtained when minimizing TOPP, AP, $NO_x$ and PE increased by approximately 50% relative to the minimum value of $SO_2$ obtained from the $SO_2$ minimization problem. This increase was mainly because the SOFC, which has a relatively higher $SO_2$ emission factor than the MT and ICE cogeneration systems, was used to meet part of the energy demand. The higher $SO_2$ values for the SOFC originated from manufacturing stage of the SOFC, where the emissions were associated with electric production from the average electric generation mix to meet the power requirements of the manufacturing process. The $SO_2$ values increased by three times (relative to the minimum value of $SO_2$ obtained from the $SO_2$ minimization problem) when minimizing GWP and $CO_2$, because the average electric grid which has a higher $SO_2$ emission factor than the MT and ICE cogeneration systems, was used to meet part of the power demand, while the use of the average electric grid as the main power supply caused the $SO_2$ value to increase by 48 times when minimizing cost.

The values of AP obtained when minimizing TOPP and $NO_x$ were approximately equal to the minimum value of AP obtained in the AP minimization problem; however, the AP values increased almost six times when minimizing PE, about ten times when minimizing GWP, $CO_2$ and $SO_2$, and about 17 times when minimizing cost. The values of $NO_x$ followed the same trend as the AP values with respect to the objective functions, i.e., the $NO_x$ values obtained when minimizing AP and TOPP were approximately equal to the minimum $NO_x$ value obtained when minimizing $NO_x$, and increased five times when minimizing PE, approximately ten times when minimizing GWP, $CO_2$ and $SO_2$ and about 13 times when minimizing cost.

The values of TOPP obtained when minimizing AP and $NO_x$ were increased by approximately 60% relative to the minimum value of TOPP obtained in the TOPP minimization problem; moreover, the values of TOPP increased approximately five times when minimizing PE, approximately ten times when minimizing GWP, $CO_2$ and $SO_2$ and about 13 times when minimizing cost. The values of PE obtained when minimizing GWP, $CO_2$ and $SO_2$, were similar to the minimum PE value obtained from the PE minimization problem; however, the PE values increased by approximately 15% when minimizing TOPP, AP, $NO_x$ and cost.

In summary, generally when minimizing the GWP, $CO_2$, $SO_2$ and PE objective functions, the results indicate that the optimum cogeneration system was the ICE cogeneration system supplying most of the energy demand while the MT cogeneration system was used to a lesser extent to supply part of the energy demand and the average electric grid was used minimally if at all. The SOFC cogeneration system was also used to meet part of the energy demand when minimizing PE in addition to the ICE and MT cogeneration systems. When minimizing the AP, TOPP and $NO_x$ objective functions, the MT and SOFC cogeneration were found to be the optimum systems to meet the energy requirement. The cogenerated heat from the cogeneration systems was found to be optimal in meeting most of the heating requirement as well as the cooling demand with absorption chillers, leading to high electric savings in the cooling months. However, when minimizing cost, it was found to be optimum to obtain power from the average electric grid except in the heating months when part of the energy demand was supplied by the ICE cogeneration system.

The results obtained from the Pareto optimal solutions for the environmental indicators and cost indicated that a decrease in GWP, $CO_2$, $SO_2$ and PE indicator values relative to the values obtained at minimum cost were achievable with relatively low increment in cost, due to the shift of energy use from the average electric grid as the main power source when minimizing cost to cogeneration systems when minimizing the environmental indicators. A 29% decrease in $CO_2$ value relative to the $CO_2$ value obtained at minimum cost was achievable with only 15% increase in cost, relative to the minimum cost value. Likewise, a 27% decrease in GWP value was attainable with only a 18% increase in cost; a 14% decrease in PE value with a 31% increase in cost if the SOFC was in use and only a 24% increase in cost if it was not in use. An approximately 98% decrease in $SO_2$ was achievable with only a 20% increase in cost, reflecting the difference between the high $SO_2$ emission factors of the average electric grid relative to the cogeneration systems. On the other hand, the decrease in TOPP, AP and $NO_x$ indicator values relative to the values obtained at minimum cost was gradual with high increment in cost values, reflecting the shift in use from the average electric grid, to ICE and MT cogeneration systems and finally, the SOFC cogeneration system, resulting in high cost. An approximately 94% decrease in AP, a 93% decrease in TOPP and a 93% decrease in $NO_x$ indicator values (relative to the values obtained at minimum cost) were attainable with a 58%, 64% and 59% increases in cost relative to the minimum cost values, respectively.

The difference in the trends between the first group of indicators: GWP, PE, $CO_2$ and $SO_2$, and the second group of indicators: TOPP, AP and $NO_x$ was mainly because, first, the cost difference between the average electric grid (which was the main source for power supply when minimizing cost) and the cost of using cogeneration systems, when minimizing the first group of indicators, was low leading to a considerable decrease in the values of the indicators with a minimal increase in cost; and second, because the difference between the indicator factors associated with the average electric grid and the cogeneration systems was significant leading to considerable decrease in the values of the indicators from those obtained at minimum cost. However, with the second group of indicators (TOPP, AP and $NO_x$) the decrease in indicator values was gradual with higher increment in cost values mainly because the difference in cost between the average electric and the SOFC and MT cogeneration systems was very high.

### 6.1.2 Problem Set (II) for NGCC Power Plant Utility Option

Generally, for all the objective functions the results obtained from the *Simplified Yearly LCA Optimization Model* resembled those obtained from the *Hourly LCA Optimization Model*. The results from the *Hourly LCA Optimization Model* for the GWP and $CO_2$ minimization problems were different from the results obtained with problem set (I) for the average electric grid option due to the lower GWP and $CO_2$ emission factors of the NGCC power plant compared to the average electric grid. With these lower life cycle emission factors, NGCC was competitive with the cogeneration systems. When minimizing GWP, the NGCC power plant provided 40-60% of the power demand, with its use greater in the cooling months. The remainder of the power demand was supplied by the ICE cogeneration system while the MT cogeneration system supplied less than 10% of the power demand in the heating months. Because the $CO_2$ emission factor of the NGCC approached that of the ICE cogeneration system, the proportion of power supplied by the NGCC decreased while the ICE cogeneration systems increased its power supply proportion when minimizing GWP. For both the GWP and $CO_2$ minimization problems, the heating demand was met by the cogenerated heat from the ICE and in part from the MT while the gas boiler was only used in the heating months to supplement the heating supply. The cooling demand, on the other hand, was met mainly by the electric chillers when minimizing GWP and partially by the absorption chillers. As the ICE cogeneration system use increased when minimizing $CO_2$, the cooling demand was met primarily by the absorption chillers and the electric chillers were used only in the cooling months. The results obtained from the $SO_2$ minimization problem with respect to the energy system's use are similar to the results obtained from the $CO_2$ minimization problem.

When using the *Hourly LCA Optimization Model* in the TOPP, AP and $NO_x$ minimization problems, the results were similar to those obtained for problem set (I) with the average electric grid option. It was optimum to use the SOFC and MT cogeneration systems to meet the power, heating and cooling demand of the building. This was due to the relatively lower TOPP, AP and $NO_x$ life cycle emission factors of the SOFC and MT cogeneration systems compared to the NGCC power plant emission factors.

Unlike the results from the PE minimization problem in the first problem set, where the SOFC was found to be optimum to supply part of the energy demand, the results obtained from *Hourly LCA Optimization Model* of the PE minimization problem with the NGCC power plant option indicated that it was optimum to use the ICE and NGCC power plant to supply the power demand of the building in the 12 days. The MT cogeneration system was only used minimally in the heating months in addition to the NGCC and the ICE cogeneration system which supplied most of the power demand. The NGCC power supply proportion increased in the cooling months.

The analysis of the results showed that the cogeneration systems followed the electric load of the building with no excess cogenerated heat in the heating months. Supplemental heat was provided by the gas boiler. As the cooling demand increased, the cogeneration systems continued to follow the electric load of the building while increasing their power output and began to produce excess heat. The cogeneration systems seemed to be ideal in meeting the energy demand of the building with high electric savings especially in the cooling months, where the power demand was met before reaching the peak power requirement. This was mainly because cogenerated heat was used to meet the cooling demand with an absorption chiller, in conjunction with the electric chiller. On the other hand, when minimizing cost, it was found optimum to use the NGCC power plant to meet the power demand in all the months except the heating months when part of the power demand was supplied by the ICE cogeneration system. The results showed that the energy systems reached the total peak electric demand throughout the year in order to meet the power and cooling requirement of the building and no cogeneration systems were in use in the cooling months.

As in problem set I, for the climate and building type used in the case study, the highest values of the environmental indicator objective functions occurred in the heating months of January, February and December. In the remainder of the months, the objective function values decreased as the cogeneration systems were able to meet most of the electrical as well as thermal demand without using the gas boiler. A slight increase in the objective function values occurred in the cooling months due to the increase in energy generation to meet the high cooling demand.

The results from the *Simplified Yearly LCA Optimization Model* indicated that values approximately equal to the minimum value of GWP obtained when minimizing the GWP were obtained when minimizing the $CO_2$, $SO_2$, PE and cost objective functions; however, the GWP values increased by about 80% relative to the minimum value of GWP when minimizing the TOPP, AP and $NO_x$ indicators. Similarly, approximately equal $CO_2$ values were obtained when minimizing GWP, $SO_2$, PE and cost objective functions and the $CO_2$ values increased by approximately 80% when minimizing the TOPP, AP and $NO_x$ indicators (relative to the minimum value of $CO_2$). The increase in the GWP and $CO_2$ indicator values was mainly because the SOFC was in use when minimizing the TOPP, AP and $NO_x$ indicators, which has relatively high GWP and $CO_2$ life cycle emission factors compared to the other systems. The same trend in values was obtained with $SO_2$ with respect to the objective functions. Approximately equal $SO_2$ values were obtained when minimizing the GWP, $CO_2$, PE and cost objective functions and the $SO_2$ values increased by approximately 80% when minimizing the TOPP, AP and $NO_x$ indicators (relative to the minimum value of $SO_2$).

The values of AP obtained when minimizing the TOPP and $NO_x$ indicators were approximately equal to the minimum value of AP obtained in the AP minimization problem. However, the AP values increased about four times when minimizing cost, almost seven times when minimizing the PE consumption and GWP indicators, and about eight times when minimizing $CO_2$ and $SO_2$ indicators. The values of $NO_x$ and TOPP followed the same trend as the AP values with respect to the objective functions. This trend reflected the increase in the ICE cogeneration system which has relatively higher AP, TOPP and $NO_x$ emissions to the other systems.

The values of PE obtained when minimizing the GWP, $CO_2$, $SO_2$ and cost objective functions were similar to the minimum PE value obtained from the PE minimization problem; however, the PE values increased by approximately 25% when minimizing the TOPP, AP and $NO_x$ objective functions. This was because of the relatively higher PE usage factor of the MT cogeneration system which was used to supply part of the energy demand when minimizing the TOPP, AP and $NO_x$ indicators.

In summary, unlike the results obtained from the first problem set with the average electric grid where the ICE cogeneration system supplied most of the power requirement when minimizing the GWP, $CO_2$, $SO_2$ and PE objective functions, with the NGCC option, the results indicated that the optimum systems for power supply were the NGCC supplying as much as 50% of the power demand and the ICE cogeneration system, which supplied part of the power demand and was able to meet most of the thermal demand except in the heating months when the gas boiler was used to supplement the heating supply. The MT cogeneration system was used for less than 10% of the power supply when minimizing the GWP, $CO_2$, $SO_2$ and PE objective functions; however, when minimizing the TOPP, AP and $NO_x$ objective functions, the SOFC and MT cogeneration systems were found optimum to meet all the energy demand of the building. These results are similar to those obtained from the first problem set with the average electric grid option.

The results obtained from the Pareto optimal solutions for the environmental indicators and cost indicated that nominal decreases in the GWP, $CO_2$, $SO_2$ and PE indicator values relative to the values obtained at minimum cost were obtained with relatively low increments in cost due to the shift of energy use from the NGCC as the main power source when minimizing cost to cogeneration systems when minimizing the environmental indicators. A 6% decrease in the $CO_2$ value relative to the $CO_2$ value obtained at minimum cost was obtained with only 11% increase in cost, relative to the minimum cost value. Likewise, only a 2% decrease in the GWP value was obtained with a 7% increase in cost; a 5% decrease in the $SO_2$ value was obtained with 10% increase in cost, and a 2% decrease in the PE value with a 7% increase in cost. Hence, there was no overall significant decrease in the GWP, $CO_2$, $SO_2$ and PE values relative to the values obtained at minimum cost when using cogeneration systems to replace the NGCC power supply. This was because the GWP, $CO_2$, $SO_2$, and PE emission factors of the NGCC approached those of the cogeneration systems.

On the other hand, there was a significant decrease in TOPP, AP and $NO_x$ indicator values relative to the values obtained at minimum cost. This resulted in a large increment in cost, reflecting the shift in use from the NGCC to the MT and the SOFC cogeneration systems. An approximately 78% decrease in AP, 80% decrease in TOPP and 81% decrease in AP indicator values (relative to the values obtained at minimum cost) were attainable with 74%, 81% and 75% increase in cost relative to the minimum cost values, respectively.

The difference in the trends between the first group of indicators: GWP, PE, $CO_2$ and $SO_2$, and the second group of indicators: TOPP, AP and $NO_x$ was mainly because: first, the cost difference between the NGCC (which was the main source for power supply when minimizing cost) and the cost of using cogeneration systems, when minimizing the first group of indicators, was low leading to a decrease in the values of the indicators with a minimal increase in cost; and second, because the values of the indicator factors associated with the NGCC approached those associated with the cogeneration systems (used when minimizing the indicator values), there was no significant decrease in the values of the indicators from those obtained at minimum cost. However, with the second group of indicators (TOPP, AP and $NO_x$) the decrease in indicator values was gradual with higher increment in cost values mainly because the difference in cost between the NGCC and the SOFC and MT cogeneration systems was high.

In summary, while realizing the underling the assumptions taken when modeling the energy systems, the ICE cogeneration system could present a cost effective technology to reduce the GWP, PE, $CO_2$, and $SO_2$ from the values obtained with the current conventional energy supply practice in the USA (average electric grid power, electric chillers and gas boilers). Furthermore, the use of the SOFC and MT cogeneration systems to meet the energy demand of a building could result in a significant reduction in $NO_x$ and subsequently the TOPP and AP values from the values obtained with current practice. $NO_x$ is the predominant component that influences the TOPP and AP values when comparing different gas-driven cogeneration systems because it masks the effect of $SO_2$ which is almost non existent in natural gas. Since the $NO_x$ values associated with the ICE cogeneration system are relatively higher than those associated with the SOFC and MT cogeneration system, the SOFC and MT cogeneration systems were found optimum when minimizing $NO_x$, TOPP and AP.

When improving the efficiency of the central power plant i.e. the NGCC (49% electric conversion efficiency compared to 32% of the average electric grid), as well as changing the source of fuel i.e. natural gas versus 54% coal used in the power production in the average electric generation, the results indicate that the NGCC power could be competitive with cogeneration systems when minimizing cost, GWP, PE, $CO_2$ and $SO_2$ because of the comparable emission factors associated with these indicators to those of the cogeneration systems. However, when minimizing $NO_x$, TOPP and AP, the SOFC and MT cogeneration systems remained optimum because of their higher efficiencies as well as considerably lower emission factors compared to that of associated with the NGCC.

## 6.2 CONTRIBUTIONS AND FUTURE STUDIES

The developed LCA optimization approach is useful in predicting the potential life cycle environmental impacts that might result from operating building systems such as heating, cooling, lighting, and equipment when cogeneration systems are considered. The optimization model allows for integrating utility power systems with cogeneration systems. Part load operation of the cogeneration systems is considered in the model formulation. In addition, the derived Pareto optimal frontier is useful in assessing the tradeoffs between optimizing a building's operation by minimizing the life cycle environmental impacts versus minimizing the life cycle cost.

Contributions of this research include:

- Developing an energy use/LCA/optimization framework,
- Developing an energy use optimization model based on an hourly energy use analysis in a day, and
- Developing an energy use optimization model based on a periodic energy use analysis in a year.

The two LCA optimization models are developed: the *Hourly LCA Optimization Model*, which can be used for long term planning and operational analysis in buildings, and the *Simplified Yearly LCA Optimization Model* that can be used for design and quick analysis of building operation. In addition to evaluating the potential environmental indicator and cost value, i.e., the objective function value, the solution results determine the optimal values for the decision variables expressing the quantity of hourly electrical, thermal, and cooling energy provided by each system, i.e., the optimum operational strategy. While the *Simplified Yearly LCA Optimization Model* evaluates the cumulative value of the objective function for a year, the solution of the *Hourly LCA Optimization Model* generates the minimum values of the objective function for each day in the year. This information could be used to predict the best building performance during the year based on the minimum value of the objective functions.

The developed LCA optimization models are found to be useful (considering underlying assumptions) for:

- Selecting cogeneration systems for commercial office building applications based on environmental and economic criteria;
- Flexibly optimizing the operational strategies of cogeneration systems based on the objective function by considering both thermal and electrical load following strategies instead of a single fixed strategy;
- Design and quick analysis of the building operation in an year by using the *Simplified Yearly LCA Optimization Model*;
- Detailed hourly analysis of the performance of building operation in a single day by using the *Hourly LCA Optimization Model*;
- Estimating the potential life cycle environmental impact that might result from building operation; and
- Assessing the tradeoffs between implementing cost-effective operation versus strategies that could result in lower environmental impacts.

Future studies may include:

- Implementing the LCA optimization model for different building types, sizes, campuses and locations/climates to determine their effects on the results;
- Performing parametric analyses by varying the energy systems characteristics, such as efficiencies and emissions, to examine their impacts on the results; and
- Modifying the optimization model formulation to include export of electricity produced from cogeneration systems and heat storage, to examine the effects on optimal systems.
- Constraining some of the environmental indicators when minimizing an objective function to reduce the high values of these indicators that might results when minimizing a single objective function.
- Improving the objective function to reduce the run times that occurred when solving some of the objective functions.

# APPENDIX A

## SOFC OPERATING PERFORMANCE GRAPH

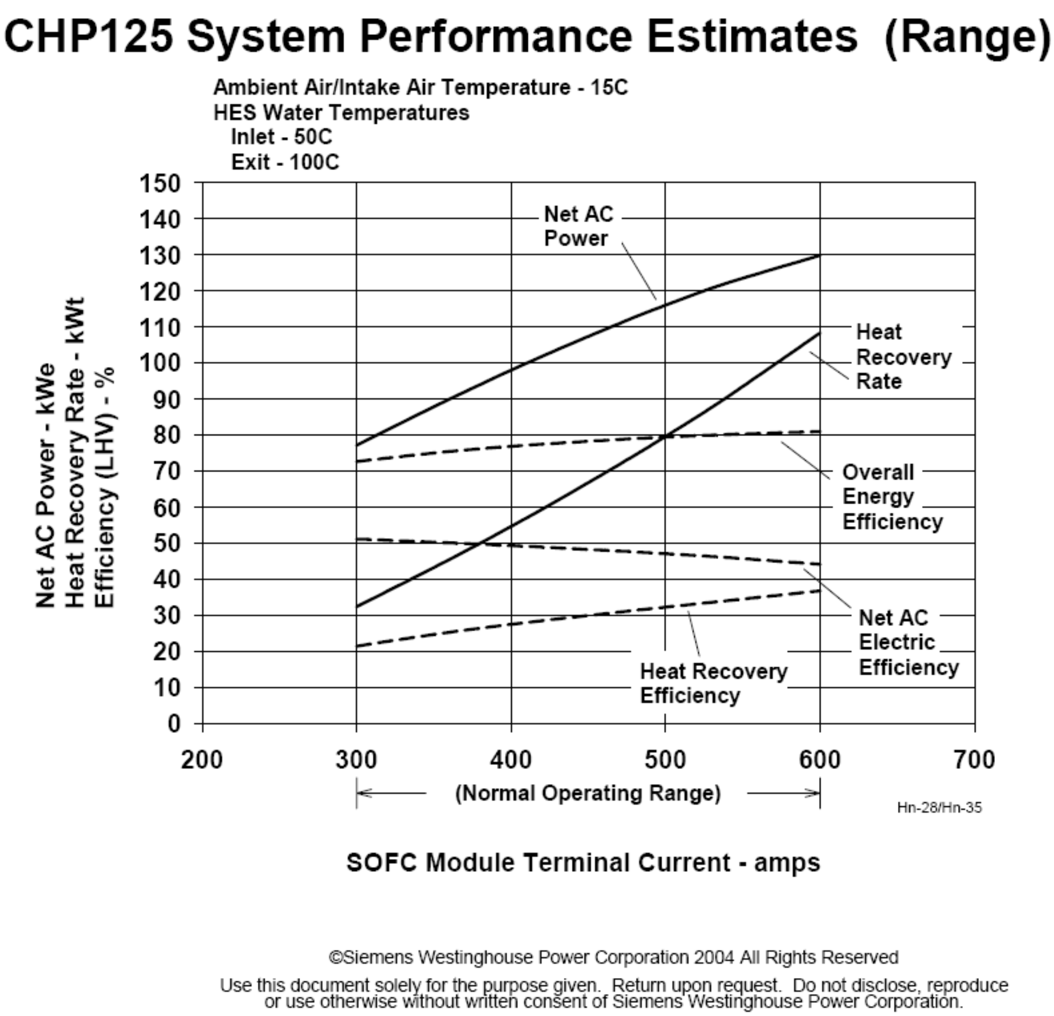



**Figure 6-1: SOFC CHP125 system performance estimates (Siemens, 2005).**

# APPENDIX B

## COST: ASSUMPTIONS & CALCULATIONS

This section includes the assumptions made in calculating the cost of cogeneration systems, the boiler and the NGCC. The capital, operating and maintenance cost of the SOFC, MT and ICE are based on cost estimates provided in the CHP technology characterization report by the EPA (EPA, 2002).

To compare the different systems, a study period of ten years is used.

The cost for electricity from the grid is obtained from US national average data (EIA, 2002). The cost of natural gas is also obtained from US national average data (EIA, 2005a).

Average electric cost = 0.0788 $/kWh.

Natural gas fuel cost = 0.0276 $/kWh (8.29 $/1000 cubic feet, where the combustion of one cubic foot of natural gas yields 0.3 kWh).

## B.1 SOFC COST CALCULATION

Estimated costs for current technology fuel cell systems in the 2003/04 timeframe (EPA, 2002).

| | |
|---|---|
| Total Installed Cost ($/kW): | 3500 |
| Stack Replacement Cost ($/kW): | 1000 |
| Variable Service Contract ($/kWh): | 0.0102 |
| Variable Consumables ($/kWh): | 0.0002 |
| Fixed Cost ($/kWh): | 0.0013 |
| Maintenance costs based on service contracts consisting of routine inspections and scheduled overhauls of the fuel cell system and are prorated based on comparable engine generator service contracts. Stack life and replacement costs are based on developers' estimates for initial units. Overall, maintenance costs are based on 8,000 annual operating hours expressed in terms of annual electricity generation. | |

The salvage, Uniform Present Value (UPV), Single Present Value (SPV), total Present Value (PV), and Uniform Capital Recovery (UCR) are calculated based on annual discount rate of 8%, equipment life and the study period of 10 years as shown in Table 6-1.

**Table 6-1: Cost calculations for SOFC at different part load operation.**

| Part load operation | 104% | 100% | 93% | 85% | 78% | 68% | 62% |
|---|---|---|---|---|---|---|---|
| Electric conversion efficiency | 44 | 45 | 48 | 49 | 50 | 50 | 51 |
| Equipment Life-time (years) | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| Equipment Capacity (kW) | 130 | 125 | 116 | 106 | 98 | 85 | 78 |
| Fuel Cost ($/kWhe) | 0.063 | 0.061 | 0.058 | 0.056 | 0.055 | 0.055 | 0.054 |
| Total Installed Cost ($) | 455000 | 437500 | 406000 | 371000 | 343000 | 297500 | 273000 |
| Stack Replacement Cost ($) | 130000 | 125000 | 116000 | 106000 | 98000 | 85000 | 78000 |
| Variable Service Contract ($) | 10608 | 10200 | 9466 | 8650 | 7997 | 6936 | 6365 |
| Variable Consumables ($) | 208 | 200 | 186 | 170 | 157 | 136 | 124.8 |
| Fixed ($/yr) | 1352 | 1300 | 1206 | 1102 | 1019 | 884 | 811.2 |
| Total O & M Cost ($/yr) | 12168 | 11700 | 10858 | 9922 | 9173 | 7956 | 7301 |
| Annual Discount Rate | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| Salvage Value ($) | 97500 | 93750 | 87000 | 79500 | 73500 | 63750 | 58500 |
| Fuel Cost ($) | 65236 | 61333 | 53360 | 47765 | 43277 | 37536 | 33769 |
| UPV (O&M) | 81648 | 78508 | 72855 | 66575 | 61550 | 53385 | 48989 |
| UPV (Fuel) | 437741 | 411552 | 358050 | 320506 | 290391 | 251870 | 226596 |
| SPV (Replacement) | 70235 | 67534 | 62671 | 57269 | 52946 | 45923 | 42141 |
| SPV (Salvage) | 45161 | 43424 | 40298 | 36824 | 34045 | 29529 | 27097 |
| PV (Total Cost) | 999463 | 951669 | 859279 | 778526 | 713843 | 619149 | 563629 |
| UCR ($) | 148949 | 141827 | 128058 | 116023 | 106384 | 92272 | 83997 |
| UCR ($/kWh) | 0.143 | 0.142 | 0.138 | 0.137 | 0.136 | 0.136 | 0.135 |

## B.2 MT COST CALCULATION

Estimated costs for the microturbine cogeneration system are estimated from the EPA technology characterization report (EPA, 2002).

| | |
|---|---|
| Total Installed Cost ($/kW): | 2031 |
| Replacement Cost ($/kW): | 1030 |
| Variable Service Contract ($/kWh): | 0.01 |

The salvage, Uniform Present Value (UPV), Single Present Value (SPV), total Present Value (PV), and Uniform Capital Recovery (UCR) are calculated based on annual discount rate of 8%, equipment life and the study period of 10 years as shown in Table 6-2.

**Table 6-2: Cost calculations for MT at different part load operation.**

| Part load operation | 100% | 75% | 50% | 25% |
|---|---|---|---|---|
| Electric conversion efficiency [%] | 26 | 24 | 20 | 13 |
| Equipment Life-time (years) | 4.6 | 4.6 | 4.6 | 4.6 |
| Fuel Cost ($/kWhe) | 0.105 | 0.114 | 0.138 | 0.211 |
| Equipment Capacity (kW) | 60 | 39.9 | 24.8 | 9.8 |
| Annual Operating Hours | 8585 | 8585 | 8585 | 8585 |
| Total Installed Cost ($) | 121860 | 81037 | 50369 | 19904 |
| Replacement Cost ($) | 61800 | 41097 | 25544 | 10094 |
| Variable Service Contract ($) | 5151 | 3425 | 2129 | 841 |
| Total O & M Cost ($/yr) | 5151 | 3425 | 2129 | 841 |
| Annual Discount Rate | 0.08 | 0.08 | 0.08 | 0.08 |
| Salvage Value ($) | 51052 | 33950 | 21102 | 8339 |
| Fuel Cost ($) @ 100% Load | 54262 | 39067 | 29381 | 17726 |
| UPV (O&M) | 34564 | 22985 | 14286 | 5645 |
| UPV (Fuel) | 364105 | 262141 | 197151 | 118941 |
| SPV (First Replacement) | 43375 | 28844 | 17928 | 7085 |
| SPV (Second Replacement) | 30443 | 20245 | 12583 | 4972 |
| SPV (Salvage) | 23647 | 15725 | 9774 | 3862 |
| PV (Total Cost) | 570700 | 399526 | 282543 | 152685 |
| UCR ($) | 85051 | 59541 | 42107 | 22755 |
| UCR ($/kWh) @ 100% Load | 0.165 | 0.174 | 0.198 | 0.270 |

## B.3 ICE COST CALCULATION

Estimated costs for the ICE cogeneration system are estimated from the EPA technology characterization report (EPA, 2002).

| | |
|---|---|
| Total Installed Cost ($/Kw): | 1515 |
| Replacement Cost ($/kW): | 260 |
| Variable Service Contract ($/kWh): | 0.017 |
| Variable Consumables ($/kWh): | 0.00015 |
| Fixed Cost ($/kWh): | 0.00125 |

The salvage, Uniform Present Value (UPV), Single Present Value (SPV), total Present Value (PV), and Uniform Capital Recovery (UCR) are calculated based on annual discount rate of 8%, equipment life and the study period of 10 years as shown in Table 6-3.

**Table 6-3: Cost calculations for ICE at different part load operation.**

| Part load operation | 100% | 75% | 50% |
|---|---|---|---|
| Electric conversion efficiency [%] | 33 | 30 | 27 |
| Equipment Life-time (years) | 4 | 4 | 4 |
| Fuel Cost ($/kWhe) | 0.083 | 0.091 | 0.104 |
| Equipment Capacity (kW) | 150 | 113 | 75 |
| Annual Operating Hours | 8000 | 8000 | 8000 |
| Total Installed Cost ($) | 227250 | 171195 | 113625 |
| Replacement Cost ($) | 39000 | 29380 | 19500 |
| Variable Service Contract ($) | 1500 | 1130 | 750 |
| Variable Consumables ($) | 180 | 136 | 90 |
| Fixed ($/yr) | 1500 | 1130 | 750 |
| Total O & M Cost ($/yr) | 3180 | 2396 | 1590 |
| Annual Discount Rate | 0.08 | 0.08 | 0.08 |
| Salvage Value ($) | 19500 | 14690 | 9750 |
| Fuel Cost ($) | 99162 | 82074 | 62256 |
| | | | |
| UPV (O&M) | 21338 | 16075 | 10669 |
| UPV (Fuel) | 665383 | 550721 | 417740 |
| SPV (First Replacement) | 28666 | 21595 | 14333 |
| SPV (Second Replacement) | 21070 | 15873 | 10535 |
| SPV (Salvage) | 9032 | 6804 | 4516 |
| PV (Total Cost) | 954675 | 768655 | 562387 |
| UCR ($) | 142275 | 114552 | 83812 |
| UCR ($/kWh) @ 100% Load | 0.119 | 0.127 | 0.140 |

## B.4 BOILER COST CALCULATION

Estimated costs for the gas boiler are estimated based on information given on the Federal Energy Management Program website for Energy Efficiency and Renewable Energy (USDOE, 2005).

| | |
|---|---|
| Total Installed Cost ($/kW) | 96.25 |
| Replacement Cost ($/kW) | 96.25 |

The salvage, Uniform Present Value (UPV), Single Present Value (SPV), total Present Value (PV), and Uniform Capital Recovery (UCR) are calculated based on annual discount rate of 8%, equipment life and the study period of 10 years as shown in Table 6-4.

**Table 6-4: Cost calculations for ICE at different part load operation.**

| Equipment | Boiler |
|---|---|
| Thermal Conversion Efficiency [%] | 80 |
| Equipment Life-time (years) | 25 |
| Equipment Capacity (kW) | 34783 |
| Annual Operating Hours | 8000 |
| Total Installed Cost ($) | 3347863.75 |
| Replacement Cost ($) | 3347863.75 |
| Annual Discount Rate | 0.08 |
| Salvage Value ($) | 2008718.25 |
| Fuel Cost ($) | 9600108 |
| UPV (Fuel) | 64417506 |
| SPV (Salvage) | 930425 |
| PV (Total Cost) | 66834945 |
| UCR ($) | 9960378 |
| UCR ($/kWh) | 0.0358 |

## B.5 NGCC COST CALCULATION

Estimated costs for the NGCC power plant are estimated based on a report for NGCC power plant cost estimates (Northwest.Power.Planning.Council, 2002).

| | |
|---|---|
| Total Installed Cost ($/kW) | 621 |
| Replacement Cost ($/kW) | 1.6 |
| Variable Service Contract ($/kWh) | 0 |
| Variable Consumables ($/kWh) | 0.002800 |
| Fixed ($/kW) | 7.25 |

The salvage, Uniform Present Value (UPV), Single Present Value (SPV), total Present Value (PV), and Uniform Capital Recovery (UCR) are calculated based on annual discount rate of 8%, equipment life and the study period of 10 years as shown in Table 6-5.

**Table 6-5: Cost calculations for NGCC at different part load operation.**

| Equipment | NGCC |
|---|---|
| Electric Conversion Efficiency [%] | 49 |
| Equipment Life-time (years) | 30 |
| Equipment Capacity (kW) | 500000 |
| Annual Operating Hours | 8059 |
| Total Installed Cost ($) | 310500000 |
| Variable Consumables ($) | 11282880 |
| Fixed ($/yr) | 3625000 |
| Total O & M Cost ($/yr) | 14907880 |
| Annual Discount Rate | 0.08 |
| Salvage Value ($) | 207000000 |
| Fuel Cost ($) | 226973388 |
| UPV (O&M) | 100033088 |
| UPV (Fuel) | 1523009907 |
| SPV (Salvage) | 95881052 |
| PV (Total Cost) | 1837661943 |
| UCR ($) | 273865820 |
| UCR ($/kWh) | 0.0680 |

# APPENDIX C

## OPTIMIZATION MODEL

This section includes the models formulations written in *Ampl* language. The model input file for the *Hourly LCA Optimization Model* is given in Figure 6-2 and the data input file is given in Figure 6-3. The model input file for the *Simplified Yearly Optimization Model* is given in Figure 6-5 and the data input file is given in Figure 6-6. Figure 6-4 shows the modified objective function and the additional parameters, variable and constraints for the modified *Hourly LCA Optimization Model* that includes the penalty for startup and shutdown of the MT cogeneration system.

The energy use data of the hypothetical office building obtained from energy simulation and used in defining the input parameters in the Hourly LCA Optimization Model and the Simplified Yearly LCA Optimization Model. The energy demand consists of:

- Electrical demand (without cooling),
- Cooling load (chiller’s efficiencies are not considered), and
- Heating load (which refers to the heating demand required for space and water heating).

Table 6-6 shows the periodical aggregation notation (shown in bold) used in defining the energy demand parameters in the data input file for the *Simplified Yearly Optimization model*, where “PERIOD” is used to define the set for periodical energy use and [*i*] is an index that used to define the time periods (aggregated data for grouped months and hours) in the set PERIOD.

**Table 6-6: Notation for periodical data aggregation used in the data file for the *Simplified Yearly Optimization Model*.**

| | **PERIOD [*i*]** | Hour Intervals |
|---|---|---|
| Average Day in January, February & December | **1** | Hr1-7 |
| | **2** | Hr 8 |
| | **3** | Hr9-17 |
| | **4** | Hr18 |
| | **5** | Hr 19-24 |
| Average Day in March & November | **6** | Hr1-7 |
| | **7** | Hr 8 |
| | **8** | Hr9-17 |
| | **9** | Hr18 |
| | **10** | Hr 19-24 |
| Average Day in April & October | **11** | Hr1-7 |
| | **12** | Hr 8 |
| | **13** | Hr9-17 |
| | **14** | Hr18 |
| | **15** | Hr 19-24 |
| Average Day in May | **16** | Hr1-7 |
| | **17** | Hr 8 |
| | **18** | Hr9-17 |
| | **19** | Hr18 |
| | **20** | Hr 19-24 |
| Average Day in June & September | **21** | Hr1-7 |
| | **22** | Hr 8 |
| | **23** | Hr9-17 |
| | **24** | Hr18 |
| | **25** | Hr 19-24 |
| Average Day in July & August | **26** | Hr1-7 |
| | **27** | Hr 8 |
| | **28** | Hr9-17 |
| | **29** | Hr18 |
| | **30** | Hr 19-24 |

```
set HOUR ordered;
set MT_TURBINE_NUMBER;
set MT_PART_LOAD;
set FC_POWER_OUTPUT;
set ENGINE_NUMBER_150;
set PART_LOAD_150;

param GWP_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param TOPP_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param AP_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param PE_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param NOX_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param CO2_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param SO2_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param COST_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param PH_RATIO_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param min_cap_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param max_cap_150  {b in ENGINE_NUMBER_150, q in PART_LOAD_150} >= min_cap_150 [b,q];
param GWP_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param TOPP_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param AP_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param PE_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param NOX_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param CO2_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param SO2_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param COST_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param GWP_FC {o in FC_POWER_OUTPUT} >= 0;
param TOPP_FC {o in FC_POWER_OUTPUT} >= 0;
param AP_FC {o in FC_POWER_OUTPUT} >= 0;
param PE_FC {o in FC_POWER_OUTPUT} >= 0;
param NOX_FC {o in FC_POWER_OUTPUT} >= 0;
param CO2_FC {o in FC_POWER_OUTPUT} >= 0;
param SO2_FC {o in FC_POWER_OUTPUT} >= 0;
param COST_FC {o in FC_POWER_OUTPUT} >= 0;
param GWP_GRID >= 0;
param GWP_BOILER >= 0;
param TOPP_GRID >= 0;
param TOPP_BOILER >= 0;
param AP_GRID >= 0;
param AP_BOILER >= 0;
param PE_GRID >= 0;
param PE_BOILER >= 0;
param NOX_GRID >= 0;
param NOX_BOILER >= 0;
param CO2_GRID >= 0;
param CO2_BOILER >= 0;
param SO2_GRID >= 0;
param SO2_BOILER >= 0;
param COST_GRID >= 0;
param COST_BOILER >= 0;
param MT_PH_RATIO {MT_TURBINE_NUMBER, MT_PART_LOAD} >= 0;
param FC_PH_RATIO {o in FC_POWER_OUTPUT} >= 0;
param MT_min_cap {MT_TURBINE_NUMBER, MT_PART_LOAD} >= 0;
param MT_max_cap  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= MT_min_cap [t,p];
param FC_min_cap {o in FC_POWER_OUTPUT} >= 0;
param FC_max_cap  {o in FC_POWER_OUTPUT} >= FC_min_cap [o];
param P {h in HOUR} >= 0;
param H {h in HOUR} >= 0;
param C {h in HOUR} >= 0;
```

*Note: Model continues in the next* page.

```
var P_ICE_SOURCE_150 {ENGINE_NUMBER_150, PART_LOAD_150, HOUR} binary;
var P_ICE_SUPPLIED_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, h in HOUR} >= 0;
var H_ICE_SUPPLIED_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, h in HOUR} >= 0;
var P_MT_SOURCE {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, h in HOUR} binary;
var P_FC_SOURCE {o in FC_POWER_OUTPUT, h in HOUR} binary;
var H_BOILER_SUPPLIED {h in HOUR} >= 0;
var P_GRID_SUPPLIED  {h in HOUR} >= 0;
var P_MT_SUPPLIED {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, h in HOUR} >= 0;
var H_MT_SUPPLIED {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, h in HOUR} >= 0;
var P_FC_SUPPLIED {o in FC_POWER_OUTPUT, h in HOUR} >= 0;
var H_FC_SUPPLIED {o in FC_POWER_OUTPUT, h in HOUR} >= 0;
var P_E {h in HOUR} >= 0;
var C_E {h in HOUR} >= 0;
var C_A {h in HOUR} >= 0;
var H_A {h in HOUR} >= 0;
var P_EXCESS {h in HOUR} >=0;
var H_EXCESS {h in HOUR} >=0;
var TOTAL_GWP;
var TOTAL_TOPP;
var TOTAL_PE;
var TOTAL_NOX;
var TOTAL_CO2;
var TOTAL_SO2;
var TOTAL_COST;

#Objective function
minimize TOTAL_AP:
sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,h] * AP_MT [t,p]) +
(sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] * AP_ICE_150 [b,q]) +
(sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * AP_FC [o])  +
(AP_GRID * P_GRID_SUPPLIED [h]) + (AP_BOILER * H_BOILER_SUPPLIED [h]));

#Ensure power, heating, and cooling supplied is greater than or equal to the demand
subject to P_SUPPLY {h in HOUR}: P_GRID_SUPPLIED [h]  + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h]) + sum {t
in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,h] + sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h]  >= P [h] + P_E [h];

subject to H_SUPPLY {h in HOUR}: H_BOILER_SUPPLIED [h] + (sum {o in FC_POWER_OUTPUT} H_FC_SUPPLIED [o,h]) + sum
{t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} H_MT_SUPPLIED [t,p,h] +  sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} H_ICE_SUPPLIED_150 [b,q,h] >= H [h] + H_A [h];

subject to C_SUPPLY {h in HOUR}: C_E [h] + C_A [h] = C [h];

# Relating cooling and heating for the absorption chiller
subject to Absorption_Chiller {h in HOUR}: H_A [h] = (C_A [h]/1.05);

# Relating cooling and electricity for electric chiller
subject to Electric_Chiller {h in HOUR}: P_E [h] = (C_E [h]/4.58);

#Introducing Excess variable for excess heat and power generated from cogeneration systems
subject to Excess_Power {h in HOUR}: (P_GRID_SUPPLIED [h]  + sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] + sum
{t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,h] + sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] ) - (P [h] + P_E [h]) = P_EXCESS [h];

subject to Excess_HEAT {h in HOUR}: (H_BOILER_SUPPLIED [h]  + sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD}
H_MT_SUPPLIED [t,p,h] +  sum {o in FC_POWER_OUTPUT} H_FC_SUPPLIED [o,h] + sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} H_ICE_SUPPLIED_150 [b,q,h] ) - (H [h] + H_A [h]) = H_EXCESS [h];

#Relating power and heat from cogeneration systems
subject to MT {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD,h in HOUR}: P_MT_SUPPLIED [t,p,h] = H_MT_SUPPLIED
[t,p,h] * MT_PH_RATIO [t,p];

subject to FC {h in HOUR, o in FC_POWER_OUTPUT}: P_FC_SUPPLIED [o,h] = H_FC_SUPPLIED [o,h] * FC_PH_RATIO [o];

subject to ICE_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150,h in HOUR}: P_ICE_SUPPLIED_150 [b,q,h] =
H_ICE_SUPPLIED_150 [b,q,h] * PH_RATIO_150 [b,q];
```

*Note: Model continues in the next* page.

```
# Relating quantity of power from a cogeneration unit and the maximum/minimum capacity is using a binary variable
subject to MT_Min_capacity {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, h in HOUR}: P_MT_SUPPLIED [t,p,h] >=
MT_min_cap [t,p] * P_MT_SOURCE [t,p,h];
subject to MT_Max_capacity {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, h in HOUR}: P_MT_SUPPLIED [t,p,h] <=
MT_max_cap [t,p] * P_MT_SOURCE [t,p,h];

subject to FC_Min_capacity {o in FC_POWER_OUTPUT, h in HOUR}: P_FC_SUPPLIED [o,h] >= FC_min_cap [o] * P_FC_SOURCE
[o,h];
subject to FC_Max_capacity {o in FC_POWER_OUTPUT, h in HOUR}: P_FC_SUPPLIED [o,h] <= FC_max_cap [o] * P_FC_SOURCE
[o,h];
subject to Min_capacity_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, h in HOUR}: P_ICE_SUPPLIED_150 [b,q,h] >=
min_cap_150 [b,q] * P_ICE_SOURCE_150 [b,q,h];
subject to Max_capacity_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, h in HOUR}: P_ICE_SUPPLIED_150 [b,q,h] <=
max_cap_150 [b,q] * P_ICE_SOURCE_150 [b,q,h];

#constraining the operation of cogeneration systems to ensure sequential use of units
subject to MT_sequential_output {t in MT_TURBINE_NUMBER, h in HOUR: t < 10}: sum {p in MT_PART_LOAD}
P_MT_SUPPLIED [t,p,h] >= sum {p in MT_PART_LOAD} P_MT_SUPPLIED [t+1,p,h];
subject to sequential_output_150 {b in ENGINE_NUMBER_150, h in HOUR: b <6}: sum {q in PART_LOAD_150}
P_ICE_SUPPLIED_150 [b,q,h] >= sum {q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b+1,q,h];
#Number of MT-level of a certain MT used at a particular hour must be less than or equal to one
subject to MT_LOADLEVEL {t in MT_TURBINE_NUMBER, h in HOUR}: sum {p in MT_PART_LOAD} P_MT_SOURCE [t,p,h] <=
1;

#Number of FC-level used at a particular hour must be less than or equal to one
subject to FC_LOADLEVEL {h in HOUR}: sum {o in FC_POWER_OUTPUT} P_FC_SOURCE [o,h] <= 1;
#Number of ICE-level used at a particular hour must be less than or equal to one
subject to ICE_LOADLEVEL_150 {b in ENGINE_NUMBER_150, h in HOUR}: sum {q in PART_LOAD_150} P_ICE_SOURCE_150
[b,q,h] <= 1;
#constraint ensures continuous operation of SOFC
subject to Operation {h in HOUR : h > 1}: sum {o in FC_POWER_OUTPUT} P_FC_SOURCE [o,h] = sum {o in
FC_POWER_OUTPUT} P_FC_SOURCE  [o,h-1];

#calculate other indicators
subject to TOPP_EMISSIONS: sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED
[t,p,h] * TOPP_MT [t,p]) + (sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] *
TOPP_ICE_150 [b,q]) + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * TOPP_FC [o])  + (TOPP_GRID *
P_GRID_SUPPLIED [h]) + (TOPP_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_TOPP;

subject to GWP_EMISSIONS:  sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED
[t,p,h] * GWP_MT [t,p]) + (sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] *
GWP_ICE_150 [b,q]) + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * GWP_FC [o])  + (GWP_GRID *
P_GRID_SUPPLIED [h]) + (GWP_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_GWP;

subject to PE_EMISSIONS: sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED
[t,p,h] * PE_MT [t,p]) + (sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] * PE_ICE_150
[b,q]) + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [h]) +
(PE_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_PE;

subject to NOX_EMISSIONS : sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED
[t,p,h] * NOX_MT [t,p]) +(sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] *
NOX_ICE_150 [b,q]) +(sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * NOX_FC [o])  + (NOX_GRID *
P_GRID_SUPPLIED [h]) + (NOX_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_NOX;

subject to CO2_EMISSIONS: sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED
[t,p,h] * CO2_MT [t,p]) + (sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] *
CO2_ICE_150 [b,q]) + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * CO2_FC [o])  + (CO2_GRID *
P_GRID_SUPPLIED [h]) + (CO2_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_CO2;

subject to SO2_EMISSIONS: sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED
[t,p,h] * SO2_MT [t,p]) + (sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] * SO2_ICE_150
[b,q]) + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * SO2_FC [o])  +  (SO2_GRID * P_GRID_SUPPLIED [h]) +
(SO2_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_SO2;

subject to COST: sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,h] *
COST_MT [t,p]) + (sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] * COST_ICE_150
[b,q]) + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * COST_FC [o])  + (COST_GRID * P_GRID_SUPPLIED [h]) +
(COST_BOILER * H_BOILER_SUPPLIED [h])) = TOTAL_COST;
end;
```

**Figure 6-2: Hourly *LCA Optimization* Model.**

```
set HOUR := 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24;
set MT_TURBINE_NUMBER := 1, 2, 3, 4, 5, 6, 7, 8, 9, 10;
set MT_PART_LOAD := 100, 75, 50, 25;
set FC_POWER_OUTPUT := 130-125, 125-116, 116-106, 106-98, 98-85, 85-78, 78;
set ENGINE_NUMBER_150 := 1, 2, 3, 4, 5, 6;
set PART_LOAD_150 := 100, 75, 50;

param GWP_GRID :=  0.787;
param GWP_BOILER := 0.24;
param GWP_ICE_150 (tr):      1          2          3          4          5          6          :=
                   100       0.620      0.620      0.620      0.620      0.620      0.620
                   75        0.675      0.675      0.675      0.675      0.675      0.675
                   50        0.764      0.764      0.764      0.764      0.764      0.764      ;
param GWP_MT (tr): 1         2          3          4          5          6          7          8          9          10  :=
          100      0.750     0.750      0.750      0.750      0.750      0.750      0.750      0.750      0.750      0.750
          75       0.795     0.795      0.795      0.795      0.795      0.795      0.795      0.795      0.795      0.795
          50       1.067     1.067      1.067      1.067      1.067      1.067      1.067      1.067      1.067      1.067
          25       1.480     1.480      1.480      1.480      1.480      1.480      1.480      1.480      1.480      1.480 ;
param TOPP_GRID :=  3.46E-03;
param TOPP_BOILER := 2.09E-04;
param TOPP_ICE_150 (tr):     1          2          3          4          5          6          :=
                   100       4.190E-03 4.190E-03 4.190E-03 4.190E-03 4.190E-03 4.190E-03
                   75        4.366E-03 4.366E-03 4.366E-03 4.366E-03 4.366E-03 4.366E-03
                   50        4.397E-03 4.397E-03 4.397E-03 4.397E-03 4.397E-03 4.397E-03 ;
param TOPP_MT (tr): 1        2          3          4          5          6          7          8          9          10  :=
          100      3.193E-04 3.193E-04 3.193E-04 3.193E-04 3.193E-04 3.193E-04 3.193E-04 3.193E-04 3.193E-04 3.193E-04
          75       8.107E-04 8.107E-04 8.107E-04 8.107E-04 8.107E-04 8.107E-04 8.107E-04 8.107E-04 8.107E-04 8.107E-04
          50       6.392E-03 6.392E-03 6.392E-03 6.392E-03 6.392E-03 6.392E-03 6.392E-03 6.392E-03 6.392E-03 6.392E-03
          25       3.767E-03 3.767E-03 3.767E-03 3.767E-03 3.767E-03 3.767E-03 3.767E-03 3.767E-03 3.767E-03 3.767E-03 ;
param AP_GRID := 2.61E-03;
param AP_BOILER := 9.89E-05;
param AP_ICE_150 (tr):       1          2          3          4          5          6          :=
                   100       2.120E-03 2.120E-03 2.120E-03 2.120E-03 2.120E-03 2.120E-03
                   75        2.217E-03 2.217E-03 2.217E-03 2.217E-03 2.217E-03 2.217E-03
                   50        2.232E-03 2.232E-03 2.232E-03 2.232E-03 2.232E-03 2.232E-03  ;
param AP_MT (tr):  1         2          3          4          5          6          7          8          9          10 :=
          100      1.815E-04 1.815E-04 1.815E-04 1.815E-04 1.815E-04 1.815E-04 1.815E-04 1.815E-04 1.815E-04 1.815E-04
          75       1.993E-04 1.993E-04 1.993E-04 1.993E-04 1.993E-04 1.993E-04 1.993E-04 1.993E-04 1.993E-04 1.993E-04
          50       2.600E-04 2.600E-04 2.600E-04 2.600E-04 2.600E-04 2.600E-04 2.600E-04 2.600E-04 2.600E-04 2.600E-04
          25       4.667E-04 4.667E-04 4.667E-04 4.667E-04 4.667E-04 4.667E-04 4.667E-04 4.667E-04 4.667E-04 4.667E-04 ;
param PE_GRID :=  3.088;
param PE_BOILER := 1.177;
param PE_ICE_150 (tr):       1          2          3          4          5          6          :=
                   100       3.129      3.129      3.129      3.129      3.129      3.129
                   75        3.438      3.438      3.438      3.438      3.438      3.438
                   50        3.927      3.927      3.927      3.927      3.927      3.927      ;
param PE_MT (tr):  1         2          3          4          5          6          7          8          9          10 :=
          100      3.987     3.987      3.987      3.987      3.987      3.987      3.987      3.987      3.987      3.987
          75       4.316     4.316      4.316      4.316      4.316      4.316      4.316      4.316      4.316      4.316
          50       5.222     5.222      5.222      5.222      5.222      5.222      5.222      5.222      5.222      5.222
          25       7.972     7.972      7.972      7.972      7.972      7.972      7.972      7.972      7.972      7.972 ;
param NOX_GRID :=  2.553E-03;
param NOX_BOILER := 1.349E-04;
param NOX_ICE_150 (tr):      1          2          3          4          5          6          :=
                   100       3.026E-03 3.026E-03 3.026E-03 3.026E-03 3.026E-03 3.026E-03
                   75        3.163E-03 3.163E-03 3.163E-03 3.163E-03 3.163E-03 3.163E-03
                   50        3.183E-03 3.183E-03 3.183E-03 3.183E-03 3.183E-03 3.183E-03 ;
param NOX_MT (tr): 1         2          3          4          5          6          7          8          9          10 :=
          100      2.337E-04 2.337E-04 2.337E-04 2.337E-04 2.337E-04 2.337E-04 2.337E-04 2.337E-04 2.337E-04 2.337E-04
          75       2.571E-04 2.571E-04 2.571E-04 2.571E-04 2.571E-04 2.571E-04 2.571E-04 2.571E-04 2.571E-04 2.571E-04
          50       3.384E-04 3.384E-04 3.384E-04 3.384E-04 3.384E-04 3.384E-04 3.384E-04 3.384E-04 3.384E-04 3.384E-04
          25       6.174E-04 6.174E-04 6.174E-04 6.174E-04 6.174E-04 6.174E-04 6.174E-04 6.174E-04 6.174E-04 6.174E-04 ;
param CO2_GRID :=  7.360E-01;
param CO2_BOILER := 2.347E-01;
param CO2_ICE_150 (tr):      1          2          3          4          5          6          :=
                   100       0.539      0.539      0.539      0.539      0.539      0.539
                   75        0.592      0.592      0.592      0.592      0.592      0.592
                   50        0.677      0.677      0.677      0.677      0.677      0.677      ;
```

*Note: data file continues in the next page.*

```
param CO2_MT (tr):  1          2          3          4          5          6          7          8          9          10 :=
          100       0.733      0.733      0.733      0.733      0.733      0.733      0.733      0.733      0.733      0.733
          75        0.770      0.770      0.770      0.770      0.770      0.770      0.770      0.770      0.770      0.770
          50        0.896      0.896      0.896      0.896      0.896      0.896      0.896      0.896      0.896      0.896
          25        1.384      1.384      1.384      1.384      1.384      1.384      1.384      1.384      1.384      1.384 ;
param SO2_GRID :=  7.768E-04;
param SO2_BOILER := 4.827E-06;
param SO2_ICE_150 (tr):        1          2          3          4          5          6          :=
                    100        1.336E-05 1.336E-05 1.336E-05 1.336E-05 1.336E-05 1.336E-05
                    75         1.454E-05 1.454E-05 1.454E-05 1.454E-05 1.454E-05 1.454E-05
                    50         1.568E-05 1.568E-05 1.568E-05 1.568E-05 1.568E-05 1.568E-05 ;

param SO2_MT (tr):  1          2          3          4          5          6          7          8          9          10 :=
          100       1.833E-05 1.833E-05 1.833E-05 1.833E-05 1.833E-05 1.833E-05 1.833E-05 1.833E-05 1.833E-05 1.833E-05
          75        1.981E-05 1.981E-05 1.981E-05 1.981E-05 1.981E-05 1.981E-05 1.981E-05 1.981E-05 1.981E-05 1.981E-05
          50        2.379E-05 2.379E-05 2.379E-05 2.379E-05 2.379E-05 2.379E-05 2.379E-05 2.379E-05 2.379E-05 2.379E-05
          25        3.593E-05 3.593E-05 3.593E-05 3.593E-05 3.593E-05 3.593E-05 3.593E-05 3.593E-05 3.593E-05 3.593E-05 ;
param COST_GRID := 0.0788;
param COST_BOILER := 0.0358;
param COST_ICE_150 (tr):       1          2          3          4          5          6          :=
                    100        0.119      0.119      0.119      0.119      0.119      0.119
                    75         0.127      0.127      0.127      0.127      0.127      0.127
                    50         0.140      0.140      0.140      0.140      0.140      0.140      ;
param COST_MT (tr): 1          2          3          4          5          6          7          8          9          10   :=
          100       0.165      0.165      0.165      0.165      0.165      0.165      0.165      0.165      0.165      0.165
          75        0.174      0.174      0.174      0.174      0.174      0.174      0.174      0.174      0.174      0.174
          50        0.198      0.198      0.198      0.198      0.198      0.198      0.198      0.198      0.198      0.198
          25        0.270      0.270      0.270      0.270      0.270      0.270      0.270      0.270      0.270      0.270;
param PH_RATIO_150 (tr) :      1          2          3          4          5          6          :=
                    100        0.609      0.609      0.609      0.609      0.609      0.609
                    75         0.526      0.526      0.526      0.526      0.526      0.526
                    50         0.438      0.438      0.438      0.438      0.438      0.438      ;
param min_cap_150 (tr) :       1          2          3          4          5          6          :=
                    100        151        151        151        151        151        151
                    75         113        113        113        113        113        113
                    50         76         76         76         76         76         76         ;
param max_cap_150 (tr):        1          2          3          4          5          6          :=
                    100        172        172        172        172        172        172
                    75         145        145        145        145        145        145
                    50         97         97         97         97         97         97         ;
param MT_PH_RATIO (tr) :
                    1          2          3          4          5          6          7          8          9          10   :=
          100       0.502      0.502      0.502      0.502      0.502      0.502      0.502      0.502      0.502      0.502
          75        0.429      0.429      0.429      0.429      0.429      0.429      0.429      0.429      0.429      0.429
          50        0.353      0.353      0.353      0.353      0.353      0.353      0.353      0.353      0.353      0.353
          25        0.226      0.226      0.226      0.226      0.226      0.226      0.226      0.226      0.226      0.226 ;
param MT_min_cap (tr) :
                    1          2          3          4          5          6          7          8          9          10  :=
          100       48         48         48         48         48         48         48         48         48         48
          75        34         34         34         34         34         34         34         34         34         34
          50        20.6       20.6       20.6       20.6       20.6       20.6       20.6       20.6       20.6       20.6
          25        9          9          9          9          9          9          9          9          9          9          ;
param MT_max_cap (tr):
                    1          2          3          4          5          6          7          8          9          10  :=
          100       54.9       54.9       54.9       54.9       54.9       54.9       54.9       54.9       54.9       54.9
          75        39.9       39.9       39.9       39.9       39.9       39.9       39.9       39.9       39.9       39.9
          50        24.8       24.8       24.8       24.8       24.8       24.8       24.8       24.8       24.8       24.8
          25        9.8        9.8        9.8        9.8        9.8        9.8        9.8        9.8        9.8        9.8  ;
param:
        FC_PH_RATIO FC_min_cap FC_max_cap GWP_FC COST_FC TOPP_FC AP_FC PE_FC NOX_FC CO2_FC SO2_FC :=
130-125   1.19      127.5      130        1.047      1.143      2.080E-04 1.230E-04 2.996      1.438E-04 1.035      2.222E-05
125-116   1.29      120.5      127.4      1.024      0.142      2.042E-04 1.209E-04 2.930      1.411E-04 1.012      2.203E-05
116-106   1.5       111        120.4      0.961      0.138      1.937E-04 1.151E-04 2.749      1.335E-04 0.949      2.150E-05
106-98    1.63      102        110.9      0.941      0.137      1.905E-04 1.133E-04 2.694      1.312E-04 0.930      2.133E-05
98-85     1.79      91.5       101.9      0.923      0.136      1.875E-04 1.116E-04 2.640      1.290E-04 0.911      2.118E-05
85-78     2.08      81.5       91.4       0.923      0.136      1.875E-04 1.116E-04 2.640      1.290E-04 0.911      2.118E-05
78        2.43      74.5       81.4       0.905      0.135      1.845E-04 1.099E-04 2.589      1.269E-04 0.894      2.103E-05 ;
```

*Note: data file continues in the next page.*

```
#JANUARY
#param:  P    H    C :=
#1       92   452  0
#2       89   462  0
#3       87   472  0
#4       84   481  0
#5       81   491  0
#6       78   499  0
#7       88   487  0
#8       160  510  0
#9       214  335  0
#10      212  218  0.72
#11      211  143  8.72
#12      211  113  22.2
#13      211  95   35.3
#14      211  82   53.8
#15      211  89   70.2
#16      212  116  63.3
#17      212  166  28.1
#18      177  260  1.57
#19      110  267  0
#20      97   331  0
#21      95   373  0
#22      93   408  0
#23      98   430  0
#24      95   448  0 ;

#FEBRUARY
#param:  P    H    C :=
#1       89   380  0
#2       86   392  0
#3       83   403  0
#4       80   415  0
#5       78   426  0
#6       75   437  0
#7       84   421  0
#8       157  387  0
#9       212  232  0.33
#10      212  135  21.19
#11      212  94   41.06
#12      212  68   64.46
#13      212  49   85.72
#14      212  47   96.92
#15      212  52   121.33
#16      212  67   120.01
#17      212  82   96.53
#18      176  127  26.83
#19      105  143  0.81
#20      91   191  0
#21      89   242  0
#22      88   296  0
#23      93   330  0
#24      91   335  0 ;
```

```
#MARCH
#param:  P    H    C :=
#1       82   241  0.02
#2       79   254  0
#3       77   268  0
#4       74   283  0
#5       71   292  0
#6       68   301  0
#7       77   275  0
#8       154  239  0.89
#9       211  126  35.17
#10      212  81   86.27
#11      213  58   130.63
#12      214  49   156.41
#13      214  39   178.35
#14      215  36   208.66
#15      215  38   222.05
#16      215  44   224.37
#17      214  55   179.91
#18      176  73   102.18
#19      104  68   25.01
#20      87   97   7.69
#21      85   135  2.87
#22      83   179  1.19
#23      87   206  0.64
#24      85   223  0.28 ;

#APRIL
#param: P     H    C :=
#1       74   53   0.01
#2       71   64   0
#3       68   81   0
#4       66   96   0
#5       63   112  0
#6       60   129  0
#7       71   109  0
#8       160  81   2.13
#9       220  31   44.91
#10      221  19   124.63
#11      222  16   193.11
#12      223  17   245.70
#13      224  16   273.79
#14      224  16   314.14
#15      225  16   340.83
#16      225  17   351.85
#17      224  17   334.02
#18      185  17   271.27
#19      113  15   153.46
#20      90   14   61.62
#21      82   16   16.47
#22      76   20   4.27
#23      79   24   1.23
#24      77   53   0.21 ;
```

*Note: data file continues in the next page*

```
#MAY
#param:  P    H    C :=
#1       72   9    7.39
#2       69   13   5.04
#3       66   17   2.91
#4       63   21   1.44
#5       59   25   1.20
#6       56   31   0.99
#7       67   21   6.83
#8       157  21   62.38
#9       218  16   162.91
#10      219  16   254.78
#11      220  16   329.47
#12      221  17   369.32
#13      221  16   388.71
#14      222  16   409.42
#15      222  16   429.42
#16      222  17   442.61
#17      221  17   415.58
#18      183  14   360.89
#19      118  11   266.28
#20      93   8    147.44
#21      83   6    54.51
#22      77   6    23.19
#23      79   6    14.85
#24      76   6    10.19 ;

#JUNE
#param:  P    H    C :=
#1       73   6    26.36
#2       70   6    22.07
#3       66   6    18.73
#4       63   6    14.63
#5       59   7    11.25
#6       56   8    9.01
#7       68   6    43.98
#8       153  16   183.67
#9       211  15   303.79
#10      213  15   395.42
#11      214  15   469.98
#12      215  17   506.62
#13      215  15   517.26
#14      215  15   536.00
#15      215  15   547.58
#16      216  17   573.64
#17      216  17   562.87
#18      179  13   495.14
#19      120  10   410.82
#20      97   8    264.56
#21      86   6    124.07
#22      79   6    63.97
#23      81   6    44.39
#24      77   6    33.66 ;
```

```
#JULY
#param:  P    H    C :=
#1       75   6    59.99
#2       71   6    52.14
#3       68   6    45.14
#4       64   6    38.17
#5       60   6    31.29
#6       57   6    27.18
#7       69   6    64.20
#8       159  17   235.80
#9       220  16   371.64
#10      221  16   482.57
#11      223  16   574.90
#12      223  17   647.77
#13      223  16   683.33
#14      223  16   697.94
#15      223  16   728.99
#16      224  17   762.23
#17      224  17   756.32
#18      186  14   663.61
#19      128  11   552.04
#20      102  8    357.96
#21      90   6    192.35
#22      82   6    119.28
#23      83   6    90.84
#24      79   6    74.01 ;

#AUGUST
#param:  P    H    C :=
#1       74   6    49.07
#2       71   6    40.20
#3       67   6    33.74
#4       64   6    28.75
#5       60   6    24.66
#6       57   6    21.77
#7       68   6    33.35
#8       158  17   189.43
#9       220  16   342.64
#10      222  16   459.28
#11      223  16   566.92
#12      224  17   625.97
#13      224  16   651.68
#14      223  16   673.62
#15      224  16   702.63
#16      224  17   727.41
#17      224  17   707.16
#18      185  14   588.30
#19      124  11   452.40
#20      97   8    254.10
#21      87   6    131.96
#22      80   6    83.94
#23      82   6    65.27
#24      78   6    55.16 ;
```

*Note: data file continues in the next page*

```
#SEPTEMBER
#param:   P     H     C :=
#1        73    6     15.79
#2        69    6     12.37
#3        66    7     9.60
#4        63    9     7.38
#5        59    12    5.63
#6        56    15    4.47
#7        66    18    7.69
#8        152   19    79.09
#9        210   15    172.75
#10       213   15    284.30
#11       214   15    379.48
#12       215   17    429.83
#13       216   15    467.77
#14       216   15    493.14
#15       216   15    522.87
#16       216   17    541.31
#17       216   17    504.06
#18       178   13    389.05
#19       114   10    256.96
#20       90    8     121.89
#21       83    6     64.96
#22       77    6     35.70
#23       80    6     25.29
#24       76    6     20.01 ;

#OCTOBER
#param:   P     H     C :=
#1        74    55    0.17
#2        71    68    0.18
#3        68    83    0.26
#4        66    96    0.07
#5        63    110   0
#6        60    123   0
#7        71    125   0
#8        156   111   2.57
#9        215   29    24.44
#10       216   16    106.89
#11       217   16    208.19
#12       219   17    279.93
#13       219   16    320.89
#14       220   16    351.37
#15       221   16    375.94
#16       220   17    372.37
#17       219   17    323.67
#18       181   14    224.40
#19       107   11    70.13
#20       85    8     16.33
#21       80    7     4.15
#22       75    14    1.13
#23       79    29    0.42
#24       77    44    0.19 ;
```

```
#NOVEMBER
#param:   P     H     C :=
#1        82    233   0
#2        79    241   0
#3        76    249   0
#4        73    257   0
#5        70    264   0
#6        67    271   0
#7        76    254   0
#8        150   222   0
#9        204   110   11.56
#10       203   56    39.68
#11       203   34    66.58
#12       204   29    106.10
#13       204   28    137.28
#14       205   25    156.69
#15       205   34    168.28
#16       204   46    140.65
#17       203   64    76.16
#18       168   83    15.57
#19       100   82    2.25
#20       86    119   0.10
#21       85    159   0
#22       83    197   0
#23       88    222   0
#24       85    237   0 ;

#DECEMBER
#param:   P     H     C :=
#1        89    381   0
#2        86    390   0
#3        83    399   0
#4        80    406   0
#5        77    411   0
#6        74    418   0
#7        84    409   0
#8        158   431   0
#9        213   284   0
#10       212   186   4.72
#11       211   128   15.47
#12       211   99    28.89
#13       211   89    57.48
#14       212   81    78.48
#15       213   79    81.01
#16       212   93    51.94
#17       211   141   15.62
#18       175   200   6.12
#19       108   198   0.34
#20       94    263   0
#21       92    306   0
#22       90    338   0
#23       94    354   0
#24       91    364   0 ;
```

*Note: the model is solved for each day in a month at a time and one objective function at a time.*

**Figure 6-3: Data input file for the *Hourly LCA Optimization Model*.**

```
param PENALTY_MT_GWP {t in MT_TURBINE_NUMBER} >= 0, default 7.87;
param PENALTY_MT_TOPP {t in MT_TURBINE_NUMBER} >= 0, default 3.46E-02;
param PENALTY_MT_AP {t in MT_TURBINE_NUMBER} >= 0, default 2.61E-02;
param PENALTY_MT_PE {t in MT_TURBINE_NUMBER} >= 0, default 30.9;
param PENALTY_MT_NOX {t in MT_TURBINE_NUMBER} >= 0, default 2.55E-02;
param PENALTY_MT_CO2 {t in MT_TURBINE_NUMBER} >= 0, default 7.36;
param PENALTY_MT_SO2 {t in MT_TURBINE_NUMBER} >= 0, default 7.77E-03;
param PENALTY_MT_COST {t in MT_TURBINE_NUMBER} >= 0, default 0.788 ;

var PENALTY_MT_APPLIED {t in MT_TURBINE_NUMBER, h in HOUR} binary;

#objective function

minimize TOTAL_AP:
sum {h in HOUR} ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,h] * AP_MT [t,p]) +
(sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,h] * AP_ICE_150 [b,q]) +
(sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,h] * AP_FC [o])  +
            (AP_GRID * P_GRID_SUPPLIED [h]) + (AP_BOILER * H_BOILER_SUPPLIED [h])) +

(sum {t in MT_TURBINE_NUMBER} PENALTY_MT_APPLIED [t,h] * PENALTY_MT_AP [t]));

#penalty for shutdown and startup of turbines
subject to PENALTY_A {t in MT_TURBINE_NUMBER, h in HOUR: h > 1}: PENALTY_MT_APPLIED [t,h] >= (sum {p in
MT_PART_LOAD} P_MT_SOURCE [t,p,h]-sum {p in MT_PART_LOAD} P_MT_SOURCE [t,p,h-1]);

subject to PENALTY_B {t in MT_TURBINE_NUMBER, h in HOUR: h > 1}: PENALTY_MT_APPLIED [t,h] >= (sum {p in
MT_PART_LOAD} P_MT_SOURCE [t,p,h-1]-sum {p in MT_PART_LOAD} P_MT_SOURCE [t,p,h]);
```

*Note: the other parameters, variables and constraints, as well as the data input file given in Figure 6-3, are the same as those given in the Hourly LCA Optimization Model* (Figure 6-2).

**Figure 6-4: Modified *Hourly LCA Optimization Model* to include penalty for MT startup/shutdown.**

```
set PERIOD;
set MT_TURBINE_NUMBER;
set MT_PART_LOAD;
set FC_POWER_OUTPUT;
set ENGINE_NUMBER_150;
set PART_LOAD_150;

param GWP_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param TOPP_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param AP_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param PE_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param NOX_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param CO2_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param SO2_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param COST_ICE_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param PH_RATIO_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param min_cap_150 {ENGINE_NUMBER_150, PART_LOAD_150} >= 0;
param max_cap_150  {b in ENGINE_NUMBER_150, q in PART_LOAD_150} >= min_cap_150 [b,q];
param GWP_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param TOPP_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param AP_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param PE_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param NOX_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param CO2_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param SO2_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param COST_MT  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= 0;
param GWP_FC {o in FC_POWER_OUTPUT} >= 0;
param TOPP_FC {o in FC_POWER_OUTPUT} >= 0;
param AP_FC {o in FC_POWER_OUTPUT} >= 0;
param PE_FC {o in FC_POWER_OUTPUT} >= 0;
param NOX_FC {o in FC_POWER_OUTPUT} >= 0;
param CO2_FC {o in FC_POWER_OUTPUT} >= 0;
param SO2_FC {o in FC_POWER_OUTPUT} >= 0;
param COST_FC {o in FC_POWER_OUTPUT} >= 0;
param GWP_GRID >= 0;
param GWP_BOILER >= 0;
param TOPP_GRID >= 0;
param TOPP_BOILER >= 0;
param AP_GRID >= 0;
param AP_BOILER >= 0;
param PE_GRID >= 0;
param PE_BOILER >= 0;
param NOX_GRID >= 0;
param NOX_BOILER >= 0;
param CO2_GRID >= 0;
param CO2_BOILER >= 0;
param SO2_GRID >= 0;
param SO2_BOILER >= 0;
param COST_GRID >= 0;
param COST_BOILER >= 0;
param MT_PH_RATIO {MT_TURBINE_NUMBER, MT_PART_LOAD} >= 0;
param FC_PH_RATIO {o in FC_POWER_OUTPUT} >= 0;
param MT_min_cap {MT_TURBINE_NUMBER, MT_PART_LOAD} >= 0;
param MT_max_cap  {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} >= MT_min_cap [t,p];
param FC_min_cap {o in FC_POWER_OUTPUT} >= 0;
param FC_max_cap  {o in FC_POWER_OUTPUT} >= FC_min_cap [o];
```

*Note: the model continues in the next page.*

```
param P {i in PERIOD} >= 0;
param H {i in PERIOD}  >= 0;
param C {i in PERIOD} >= 0;

var P_ICE_SOURCE_150 {ENGINE_NUMBER_150, PART_LOAD_150, PERIOD} binary;
var P_ICE_SUPPLIED_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, i in PERIOD} >= 0;
var H_ICE_SUPPLIED_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, i in PERIOD} >= 0;
var P_MT_SOURCE {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, i in PERIOD} binary;
var P_FC_SOURCE {o in FC_POWER_OUTPUT, i in PERIOD } binary;
var H_BOILER_SUPPLIED {i in PERIOD} >= 0;
var P_GRID_SUPPLIED  {i in PERIOD} >= 0;
var P_MT_SUPPLIED {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, i in PERIOD } >= 0;
var H_MT_SUPPLIED {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, i in PERIOD } >= 0;
var P_FC_SUPPLIED {o in FC_POWER_OUTPUT, i in PERIOD } >= 0;
var H_FC_SUPPLIED {o in FC_POWER_OUTPUT, i in PERIOD } >= 0;
var P_E {i in PERIOD} >= 0;
var C_E  {i in PERIOD} >= 0;
var C_A  {i in PERIOD} >= 0;
var H_A  {i in PERIOD} >= 0;
var P_EXCESS {i in PERIOD} >=0;
var H_EXCESS  {i in PERIOD} >=0;
```

*Note: the model continues in the next page.*

```
#Objective function
minimize TOTAL_PE:
((90*((7 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,1] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,1] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,1] * PE_FC [o])  +  (PE_GRID * P_GRID_SUPPLIED [1]) + (PE_BOILER *
H_BOILER_SUPPLIED [1])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,2] * PE_MT [t,p]) +
(sum {b in ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,2] * PE_ICE_150 [b,q]) +
(sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,2] * PE_FC [o])  +
(PE_GRID * P_GRID_SUPPLIED [2]) + (PE_BOILER * H_BOILER_SUPPLIED [2]))
+ (9 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,3] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,3] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,3] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [3]) + (PE_BOILER *
H_BOILER_SUPPLIED [3])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,4] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,4] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,4] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [4]) + (PE_BOILER *
H_BOILER_SUPPLIED [4]))
+ (6 * ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,5] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,5] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,5] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [5]) + (PE_BOILER *
H_BOILER_SUPPLIED [5])))))
+ (61*((7 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,6] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,6] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,6] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [6]) + (PE_BOILER *
H_BOILER_SUPPLIED [6])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,7] * PE_MT [t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,7] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,7] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [7]) + (PE_BOILER *
H_BOILER_SUPPLIED [7]))
+ (9 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,8] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,8] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,8] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [8]) + (PE_BOILER *
H_BOILER_SUPPLIED [8])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,9] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,9] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,9] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [9]) + (PE_BOILER *
H_BOILER_SUPPLIED [9]))
+ (6 * ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,10] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,10] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,10] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [10]) + (PE_BOILER *
H_BOILER_SUPPLIED [10])))))
+ (61*((7 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,11] * PE_MT[t,p]) +  (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,11] * PE_ICE_150 [b,q]) +(sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,11] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [11]) + (PE_BOILER *
H_BOILER_SUPPLIED [11])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,12] * PE_MT [t,p]) +(sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,12] * PE_ICE_150 [b,q]) +   (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,12] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [12]) + (PE_BOILER *
H_BOILER_SUPPLIED [12]))
+ (9 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,13] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,13] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,13] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [13]) + (PE_BOILER *
H_BOILER_SUPPLIED [13])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,14] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,14] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,14] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [14]) + (PE_BOILER *
H_BOILER_SUPPLIED [14]))
+ (6 * ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,15] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,15] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,15] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [15]) + (PE_BOILER *
H_BOILER_SUPPLIED [15])))))) +
```

*Note: the model continues in the next page.*

```
(31*((7 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,16] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,16] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,16] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [16]) + (PE_BOILER *
H_BOILER_SUPPLIED [16])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,17] * PE_MT [t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,17] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,17] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [17]) + (PE_BOILER *
H_BOILER_SUPPLIED [17]))
+ (9 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,18] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,18] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,18] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [18]) + (PE_BOILER *
H_BOILER_SUPPLIED [18])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,19] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,19] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,19] * PE_FC [o])  +  (PE_GRID * P_GRID_SUPPLIED [19]) + (PE_BOILER *
H_BOILER_SUPPLIED [19]))
+ (6 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,20] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,20] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,20] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [20]) + (PE_BOILER *
H_BOILER_SUPPLIED [20])))))
+ (60*((7 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,21] * PE_MT[t,p]) +  (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,21] * PE_ICE_150 [b,q]) +   (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,21] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [21]) + (PE_BOILER *
H_BOILER_SUPPLIED [21])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,22] * PE_MT [t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,22] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,22] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [22]) + (PE_BOILER *
H_BOILER_SUPPLIED [22]))
+ (9 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,23] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,23] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,23] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [23]) + (PE_BOILER *
H_BOILER_SUPPLIED [23])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,24] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,24] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,24] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [24]) + (PE_BOILER *
H_BOILER_SUPPLIED [24]))
+ (6 * ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,25] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,25] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,25] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [25]) + (PE_BOILER *
H_BOILER_SUPPLIED [25])))))
+ (62*((7 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,26] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,26] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,26] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [26]) + (PE_BOILER *
H_BOILER_SUPPLIED [26])))
+ ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,27] * PE_MT [t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,27] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,27] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [27]) + (PE_BOILER *
H_BOILER_SUPPLIED [27]))
+ (9 *((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,28] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,28] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,28] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [28]) + (PE_BOILER *
H_BOILER_SUPPLIED [28])))
 + ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,29] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,29] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,29] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [29]) + (PE_BOILER *
H_BOILER_SUPPLIED [29]))
+ (6 * ((sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,30] * PE_MT[t,p]) + (sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,30] * PE_ICE_150 [b,q]) + (sum {o in
FC_POWER_OUTPUT} P_FC_SUPPLIED [o,30] * PE_FC [o])  + (PE_GRID * P_GRID_SUPPLIED [30]) + (PE_BOILER *
H_BOILER_SUPPLIED [30]))))));
```

*Note: the model continues in the next page.*

```
#Ensure power, heating, and cooling supplied is greater than or equal to the demand
subject to P_SUPPLY {i in PERIOD}: P_GRID_SUPPLIED [i]  + (sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,i]) + sum
{t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,i] + sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,i]  >= P [i] + P_E [i];

subject to H_SUPPLY {i in PERIOD}: H_BOILER_SUPPLIED [i] + (sum {o in FC_POWER_OUTPUT} H_FC_SUPPLIED [o,i]) +
sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} H_MT_SUPPLIED [t,p,i] +  sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} H_ICE_SUPPLIED_150 [b,q,i] >= H [i] + H_A [i];

subject to C_SUPPLY {i in PERIOD}: C_E [i] + C_A [i] = C [i];

# Relating cooling and heating for the absorption chiller
subject to Absorption_Chiller {i in PERIOD}: H_A [i] = (C_A [i]/1.05);

# Relating cooling and electricity for electric chiller
subject to Electric_Chiller {i in PERIOD}: P_E [i] = (C_E [i]/4.58);

#Introducing Excess variable for excess heat and power generated from cogeneration systems
subject to Excess_Power {i in PERIOD}: (P_GRID_SUPPLIED [i]  + sum {o in FC_POWER_OUTPUT} P_FC_SUPPLIED [o,i] +
sum {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD} P_MT_SUPPLIED [t,p,i] + sum {b in ENGINE_NUMBER_150, q in
PART_LOAD_150} P_ICE_SUPPLIED_150 [b,q,i] ) - (P [i] + P_E [i]) = P_EXCESS [i];

subject to Excess_HEAT {i in PERIOD}: (H_BOILER_SUPPLIED [i]  + sum {t in MT_TURBINE_NUMBER, p in
MT_PART_LOAD} H_MT_SUPPLIED [t,p,i] +  sum {o in FC_POWER_OUTPUT} H_FC_SUPPLIED [o,i] + sum {b in
ENGINE_NUMBER_150, q in PART_LOAD_150} H_ICE_SUPPLIED_150 [b,q,i] ) - (H [i] + H_A [i]) = H_EXCESS [i];

#Relating power and heat from cogeneration systems
subject to MT {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, i in PERIOD}: P_MT_SUPPLIED [t,p,i] =
H_MT_SUPPLIED [t,p,i] * MT_PH_RATIO [t,p];

subject to FC {i in PERIOD, o in FC_POWER_OUTPUT}: P_FC_SUPPLIED [o,h] = H_FC_SUPPLIED [o,i] * FC_PH_RATIO [o];

subject to ICE_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, i in PERIOD}: P_ICE_SUPPLIED_150 [b,q,i] =

H_ICE_SUPPLIED_150 [b,q,i] * PH_RATIO_150 [b,q];

# Relating quantity of power from a cogeneration unit and the maximum/minimum capacity is using a binary variable
subject to MT_Min_capacity {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, i in PERIOD}: P_MT_SUPPLIED [t,p,i] >=
MT_min_cap [t,p] * P_MT_SOURCE [t,p,i];
subject to MT_Max_capacity {t in MT_TURBINE_NUMBER, p in MT_PART_LOAD, i in PERIOD}: P_MT_SUPPLIED [t,p,i] <=
MT_max_cap [t,p] * P_MT_SOURCE [t,p,i];

subject to FC_Min_capacity {o in FC_POWER_OUTPUT, i in PERIOD}: P_FC_SUPPLIED [o,i] >= FC_min_cap [o] *
P_FC_SOURCE [o,i];
subject to FC_Max_capacity {o in FC_POWER_OUTPUT, i in PERIOD}: P_FC_SUPPLIED [o,i] <= FC_max_cap [o] *
P_FC_SOURCE [o,i];
subject to Min_capacity_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, i in PERIOD}: P_ICE_SUPPLIED_150 [b,q,i]
>= min_cap_150 [b,q] * P_ICE_SOURCE_150 [b,q,i];
subject to Max_capacity_150 {b in ENGINE_NUMBER_150, q in PART_LOAD_150, i in PERIOD}: P_ICE_SUPPLIED_150 [b,q,i]
<= max_cap_150 [b,q] * P_ICE_SOURCE_150 [b,q,i];

#constraining the operation of cogeneration systems to ensure sequential use of units
subject to MT_sequential_output {t in MT_TURBINE_NUMBER, i in PERIOD: t < 10}: sum {p in MT_PART_LOAD}
P_MT_SUPPLIED [t,p,i] >= sum {p in MT_PART_LOAD} P_MT_SUPPLIED [t+1,p,i];
subject to sequential_output_150 {b in ENGINE_NUMBER_150, i in PERIOD: b <6}: sum {q in PART_LOAD_150}
P_ICE_SUPPLIED_150 [b,q,i] >= sum {q in PART_LOAD_150} P_ICE_SUPPLIED_150 [b+1,q,i];
#Number of MT-level of a certain MT used at a particular period must be less than or equal to one
subject to MT_LOADLEVEL {t in MT_TURBINE_NUMBER, i in PERIOD}: sum {p in MT_PART_LOAD} P_MT_SOURCE [t,p,i]
<= 1;

#Number of FC-level used at a particular period must be less than or equal to one
subject to FC_LOADLEVEL {i in PERIOD}: sum {o in FC_POWER_OUTPUT} P_FC_SOURCE [o,i] <= 1;
#Number of ICE-level used at a particular period must be less than or equal to one
subject to ICE_LOADLEVEL_150 {b in ENGINE_NUMBER_150, i in PERIOD}: sum {q in PART_LOAD_150}
P_ICE_SOURCE_150 [b,q,i] <= 1;
#constraint ensures continuous operation of SOFC
subject to Operation {i in PERIOD : i > 1}: sum {o in FC_POWER_OUTPUT} P_FC_SOURCE [o,i] = sum {o in
FC_POWER_OUTPUT} P_FC_SOURCE  [o,i-1];
```

**Figure 6-5: Simplified *Yearly Optimization Model*.**

```
set PERIOD := 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29,30;

param:
        P       H       C  :=
1       83      430     0
2       158     442     0
3       212     125     47
4       176     196     12
5       95      313     0
6       75      263     0
7       152     231     0
8       209     53      129
9       172     78      59
10      88      160     3
11      68      93      0
12      158     96      2
13      221     18      255
14      183     16      248
15      85      21      27
16      65      20      4
17      157     21      62
18      221     16      356
19      183     14      361
20      88      7       86
21      65      8       15
22      153     17      131
23      215     16      456
24      178     13      442
25      88      7       122
26      66      6       39
27      159     17      213
28      223     16      620
29      185     14      626
30      93      7       202 ;
```

*Note: the remaining parameters are the same as those given in the Hourly LCA Optimization Model data input file (presented in Figure 6-3) except that the "set HOUR" is replaced by the "set Period."*

**Figure 6-6: Data input file for the *Simplified Yearly Optimization Model*.**

## APPENDIX D

## SENSITIVITY ANALYSIS

### D.1 PENALTY FOR MT STARTUP/SHUTDOWN

The Hourly LCA Optimization Model is modified to include a penalty for startup and shutdown of the MT cogeneration system. The time considered for MT startup and shutdown is 10 minutes. The modified model is formulated to include a penalty constraint and a penalty in the objective function, the rest of the model formulation remains the same as the Hourly LCA Optimization Model formulation given in Section 4: equations [4.2]-[4.19]. The modified objective function is as follows:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\,GRID_h \times EF\,GRID\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} MT_{uph} \times EF\,MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} ICE_{uph} \times EF\,ICE_{up}\right] \\ + \left[\sum_{p\in P} SOFC_{ph} \times EF\,SOFC_p\right] + \left[H\,BOILER_h \times EF\,BOILER\right] + \left[\sum_{u=1}^{10} MT\,PENALTY_{uh} \times EF\,PENALTYMT_u\right] \end{array} \right\} \qquad [6.1]$$

s.t.

equations: [4.2] – [4.19], [6.2] and [6.3].

where,

*MT PENALTY* $_{uh}$: is a binary variable for penalty applied to a MT unit *u* operating at hour *h*;

*EF PENALTY MT* $_{u}$: is a parameter defined for additional emissions resulting from the startup/shutdown of MT unit *u*.

The startup and shutdown penalty constraints are given in equation [6.2] and [6.3], respectively.

$$MT\ PENALTY_{uh} \geq \left[ \sum_{p \in P} BINARY\,MT_{uph} - \sum_{p \in P} BINARY\,MT_{uph\text{-}1} \right] \forall h > 1 \qquad [6.2]$$

$$MT\ PENALTY_{uh} \geq \left[ \sum_{p \in P} BINARY\,MT_{uph\text{-}1} - \sum_{p \in P} BINARY\,MT_{uph} \right] \forall h > 1 \qquad [6.3]$$

The following penalties were used in the problem formulation when each objective function was evaluated:

**Table 6-7: Penalties for MT startup/shutdown.**

| Parameter | Penalty Value |
|---|---|
| GWP Penalty [kg/kWh] | 7.87E+00 |
| | |
| TOPP Penalty [kg/kWh] | 3.46E-02 |
| | |
| AP Penalty [kg/kWh] | 2.61E-02 |
| | |
| $NO_x$ Penalty [kg/kWh] | 2.55E-02 |
| | |
| $CO_2$ Penalty [kg/kWh] | 7.36E+00 |
| | |
| $SO_2$ Penalty [kg/kWh] | 7.77E-03 |
| | |
| PE Penalty [kWh/kWh] | 3.09E+01 |
| | |
| COST Penalty [$/kWh] | 7.88E-01 |

When implementing the model (including penalty for startup/shutdown for the MT), the results didn't show much deviation from those obtained when no penalty was applied. The same equipments were used in the results of both models but the hourly operation varied. When a penalty was applied, the MT systems were operated in consecutive hours before shutdown unlike the results obtained when no penalty was used. For example, when comparing the results obtained from the model implementation with penalty for the MT startup/shutdown for minimizing GWP in October with those obtained when no penalty was applied, the same equipment were used but the variation occurred during the hourly operation of the systems during the day; that can be seen when comparing Figure 6-7, which shows the power supply from energy systems when the penalty model was used, to Figure 6-8, which shows the power supply when no penalty was used.

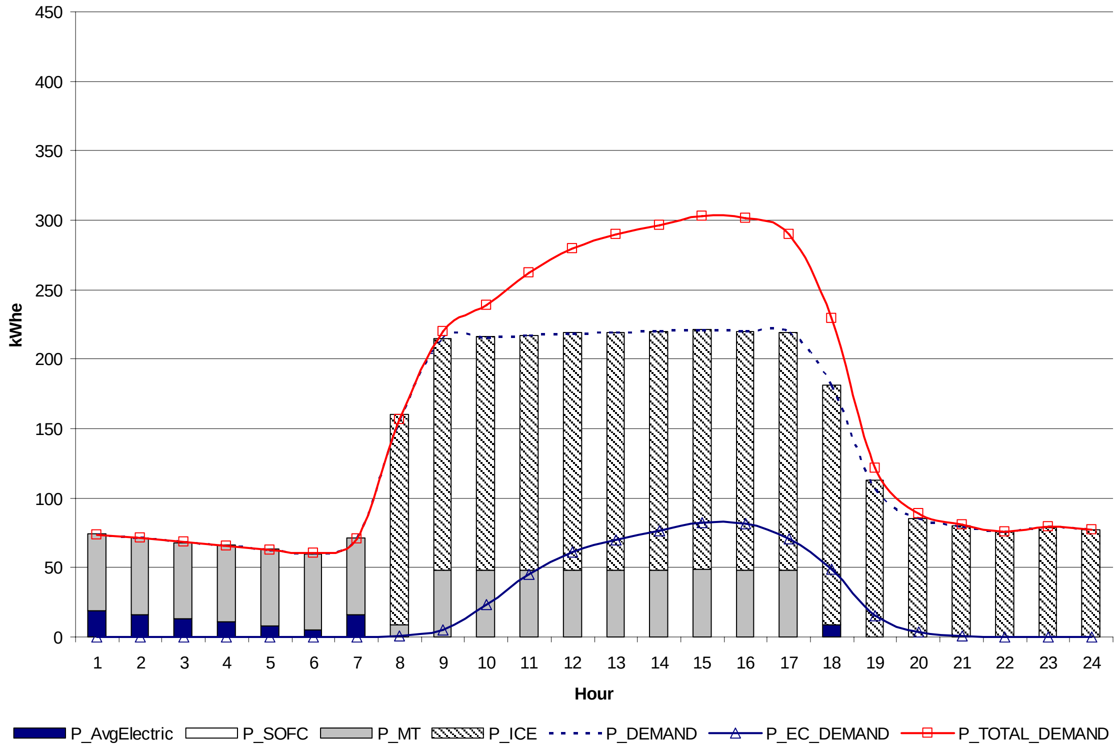



**Figure 6-7: Power supply during an average day in October when min GWP (penalty).**

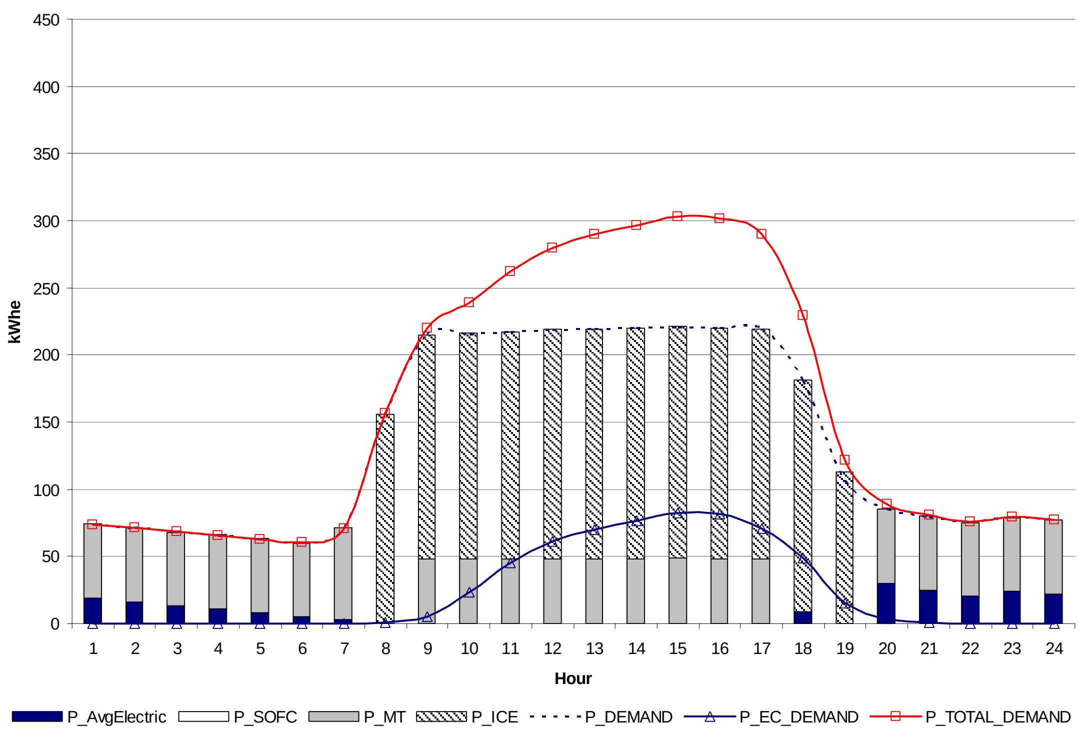



**Figure 6-8: Power supply during an average day in October when min GWP (no penalty).**

## D.2 ICE SIZES

The *Hourly LCA Optimization Model* is modified to include a several sizes of ICE cogeneration systems with various characteristics and emission factors in addition to the original systems for energy supply. The model is used to test the effects of having different ICE sizes on the operating systems chosen. The modified model is formulated to include four sizes of ICEs so that equations [4.1], [4.2] and [4.3] are modified to include the four sizes of ICE (150 kW, 350 kW, 600 kW and 2 MW) while the rest of the model formulation remains the same as the Hourly LCA Optimization Model formulation given in Section 4. The modified objective function is as follows:

$$Min \sum_{h=1}^{24} \left\{ \begin{array}{l} \left[P\,GRID_h \times EF\,GRID\right] + \left[\sum_{u=1}^{10}\sum_{p\in P} MT_{uph} \times EF\,MT_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} ICE150kW_{uph} \times EF\,ICE150kW_{up}\right] \\ + \left[\sum_{u=1}^{6}\sum_{p\in P} ICE350kW_{uph} \times EF\,ICE350kW_{up}\right] + \left[\sum_{u=1}^{6}\sum_{p\in P} ICE600kW_{uph} \times EF\,ICE600kW_{up}\right] \\ + \left[\sum_{u=1}^{6}\sum_{p\in P} ICE2MW_{uph} \times EF\,ICE2MW_{up}\right] + \left[\sum_{p\in P} SOFC_{ph} \times EF\,SOFC_{p}\right] + \left[H\,BOILER_h \times EF\,BOILER\right] \end{array} \right\} \qquad [6.4]$$

s.t.

$$\begin{array}{l} \sum_{u=1}^{10}\sum_{p\in P} P\,MT_{uph} + \sum_{u=1}^{6}\sum_{p\in P} P\_ICEkW_{uph} + \sum_{u=1}^{6}\sum_{p\in P} P\_ICE350kW_{uph} + \sum_{u=1}^{6}\sum_{p\in P} P\_ICE600kW_{uph} \\ + \sum_{u=1}^{6}\sum_{p\in P} P\_ICE2MW_{uph} + \sum_{p\in P} P\,SOFC_{ph} + P\,GRID_h \geq P_h + P\,EC_h \forall h \in H \end{array} \qquad [6.5]$$

$$\begin{array}{l} \sum_{u=1}^{10}\sum_{p\in P} H\,MT_{uph} + \sum_{u=1}^{6}\sum_{p\in P} H\_ICEkW_{uph} + \sum_{u=1}^{6}\sum_{p\in P} H\_ICE350kW_{uph} + \sum_{u=1}^{6}\sum_{p\in P} H\_ICE600kW_{uph} \\ + \sum_{u=1}^{6}\sum_{p\in P} H\_ICE2MW_{uph} + \sum_{p\in P} H\_SOFC_{ph} + H\,BOILER_h \geq H\,BOILER_h + H\,AC_h \forall h \in H \end{array} \qquad [6.6]$$

as well as equation [4.4]-[4.19]

Table 6-8 shows the efficiencies of the different ICE sizes, Table 6-9 shows the emissions from different ICEs sizes and Table 6-10 shows the LCA emission factors associated with the different ICE sizes. The ICE sizes are modeled using Caterpillar data (1999).

The results from the modified model showed that the ICE 150 kW was chosen over the other ICE sizes.  For example, when the model was implemented to minimize GWP in an average day in January, the solution of the model resembled that obtained from the Hourly LCA Optimization Model which included a single ICE size (ICE 150 kW) as shown in Figure 6-9 and 6-10.

**Table 6-8: Characteristics for different ICEs sizes.**

| | **Percent Load** | | |
|---|---|---|---|
| **ICE 350 kW** | **100%** | **75%** | **50%** |
| Engine Power (kW) | 350 | 263 | 175 |
| Engine Efficiency (%) | 35.0 | 32.9 | 29.0 |
| Thermal Efficiency (%) | 51.5 | 54.3 | 58.2 |
| Total Efficiency (%) | 86.5 | 87.1 | 87.2 |
| Power to Heat Ratio | 0.680 | 0.606 | 0.498 |
| Max Power Output | 422 | 357 | 237 |
| Min Power Output | 369 | 277 | 185 |
| **ICE 600 kW** | **100%** | **75%** | **50%** |
| Engine Power (kW) | 589 | 441 | 295 |
| Engine Efficiency (%) | 33.9 | 32.2 | 29.9 |
| Thermal Efficiency (%) | 54.8 | 54.8 | 57.4 |
| Total Efficiency (%) | 86.6 | 87.0 | 87.4 |
| Power to Heat Ratio | 0.643 | 0.588 | 0.521 |
| Max Power Output | 589 | 497 | 331 |
| Min Power Output | 151 | 386 | 258 |
| **ICE 2 MW** | **100%** | **75%** | **50%** |
| Engine Power (kW) | 2154 | 1615 | 1077 |
| Engine Efficiency (%) | 39.4 | 37.9 | 36.0 |
| Thermal Efficiency (%) | 43.2 | 44.4 | 45.5 |
| Total Efficiency (%) | 82.6 | 82.3 | 81.5 |
| Power to Heat Ratio | 0.912 | 0.854 | 0.791 |
| Max Power Output | 2154 | 1817 | 1211 |
| Min Power Output | 1885 | 1413 | 942 |

**Table 6-9: Emissions from different ICE sizes.**

| | Uncontrolled Emissions Factor (lb/MBTU) based on fuel output (LHV) | | |
|---|---|---|---|
| **ICE 350 kW** | **100% Load** | **75% Load** | **50% Load** |
| $SO_2$[a] | 1.76E-03 | 1.93E-03 | 2.21E-03 |
| $NO_x$ (as $NO_2$) | 1.84E+01 | 1.94E+01 | 1.84E+01 |
| CO | 1.30E+00 | 1.40E+00 | 1.40E+00 |
| THC | 1.60E+00 | 1.60E+00 | 2.20E+00 |
| NMVOC[a] | 2.00E-01 | 2.00E-01 | 2.00E-01 |
| $CH_4$ | 1.30E+00 | 1.30E+00 | 1.80E+00 |
| $CO_2$[b] | 3.30E+02 | 3.62E+02 | 4.14E+02 |
| **ICE 600 kW** | **100% Load** | **75% Load** | **50% Load** |
| $SO_2$[a] | 1.76E-03 | 1.93E-03 | 2.21E-03 |
| $NO_x$ (as $NO_2$) | 1.80E+01 | 1.58E+01 | 1.57E+01 |
| CO | 1.30E+00 | 1.30E+00 | 1.40E+00 |
| THC | 1.30E+00 | 1.50E+00 | 1.90E+00 |
| NMVOC[a] | 2.00E-01 | 2.00E-01 | 3.00E-01 |
| $CH_4$ | 1.10E+00 | 1.20E+00 | 1.60E+00 |
| $CO_2$[b] | 3.30E+02 | 3.62E+02 | 4.14E+02 |
| **ICE 2MW** | **100% Load** | **75% Load** | **50% Load** |
| $SO_2$[a] | 1.76E-03 | 1.93E-03 | 2.21E-03 |
| $NO_x$ (as $NO_2$) | 9.00E-01 | 9.00E-01 | 9.00E-01 |
| CO | 2.00E+00 | 2.10E+00 | 2.10E+00 |
| THC | 3.50E+00 | 4.20E+00 | 4.90E+00 |
| NMVOC[a] | 5.00E-01 | 6.00E-01 | 7.00E-01 |
| $CH_4$ | 2.90E+00 | 3.60E+00 | 4.10E+00 |
| $CO_2$ | 4.00E+02 | 4.11E+02 | 4.37E+02 |

[a] $SO_2$ emission factors are based on EPA AP 42 uncontrolled emission factors for ICE based on 100% conversion of fuel sulfur to $SO_2$.
NMVOC is not reported (CAT) but estimated by subtracting THC from methane emission factors.
[b] $CO_2$ emission factors are based on EPA AP-42 values.

**Table 6-10: LC emission factors for different ICEs sizes.**

| | Uncontrolled Emissions Factor (lb/MBTU) based on fuel output (LHV) | | |
|---|---|---|---|
| **ICE 350 kW** | **100% Load** | **75% Load** | **50% Load** |
| TOPP | 3.93E-03 | 3.95E-03 | 4.05E-03 |
| AP | 2.08E-03 | 2.09E-03 | 2.10E-03 |
| GWP | 5.53E-01 | 5.87E-01 | 6.71E-01 |
| PE | 2.99E+00 | 3.18E+00 | 3.60E+00 |
| **ICE 600 kW** | **100% Load** | **75% Load** | **50% Load** |
| TOPP | 3.86E-03 | 3.45E-03 | 3.54E-03 |
| AP | 2.04E-03 | 1.81E-03 | 1.81E-03 |
| GWP | 5.67E-01 | 5.97E-01 | 6.48E-01 |
| PE | 3.08E+00 | 3.24E+00 | 3.49E+00 |
| **ICE 2MW** | **100% Load** | **75% Load** | **50% Load** |
| TOPP | 1.94E-03 | 1.97E-03 | 2.00E-03 |
| AP | 1.02E-03 | 1.03E-03 | 1.03E-03 |
| GWP | 7.07E-01 | 7.36E-01 | 7.88E-01 |
| PE | 2.65E+00 | 2.76E+00 | 2.90E+00 |

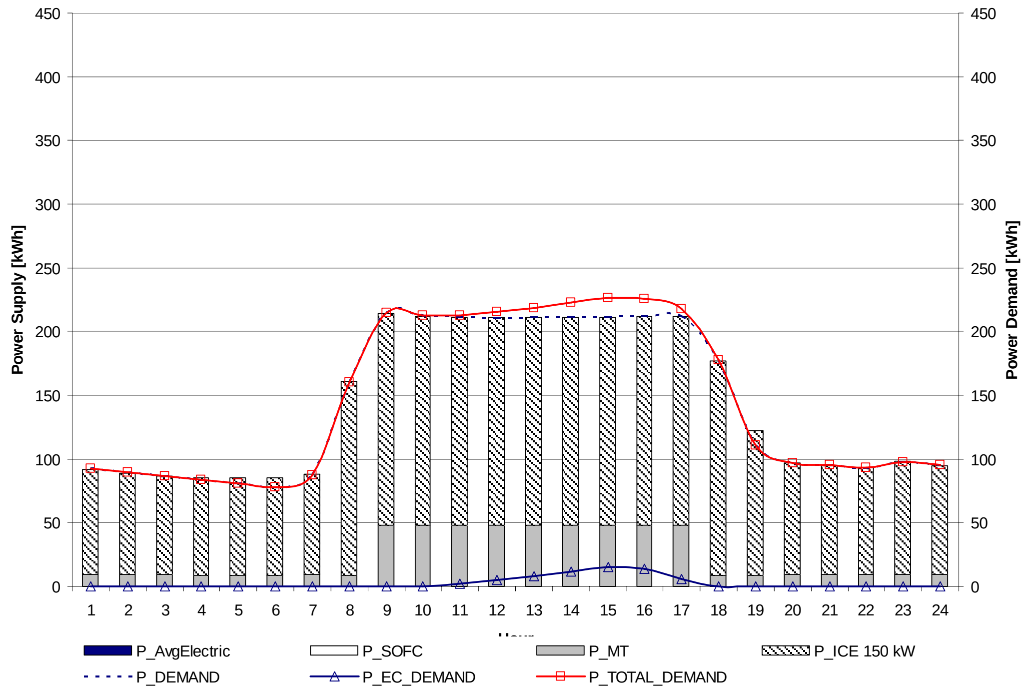



**Figure 6-9: Power supply in an average day in January for min GWP (several ICEs).**

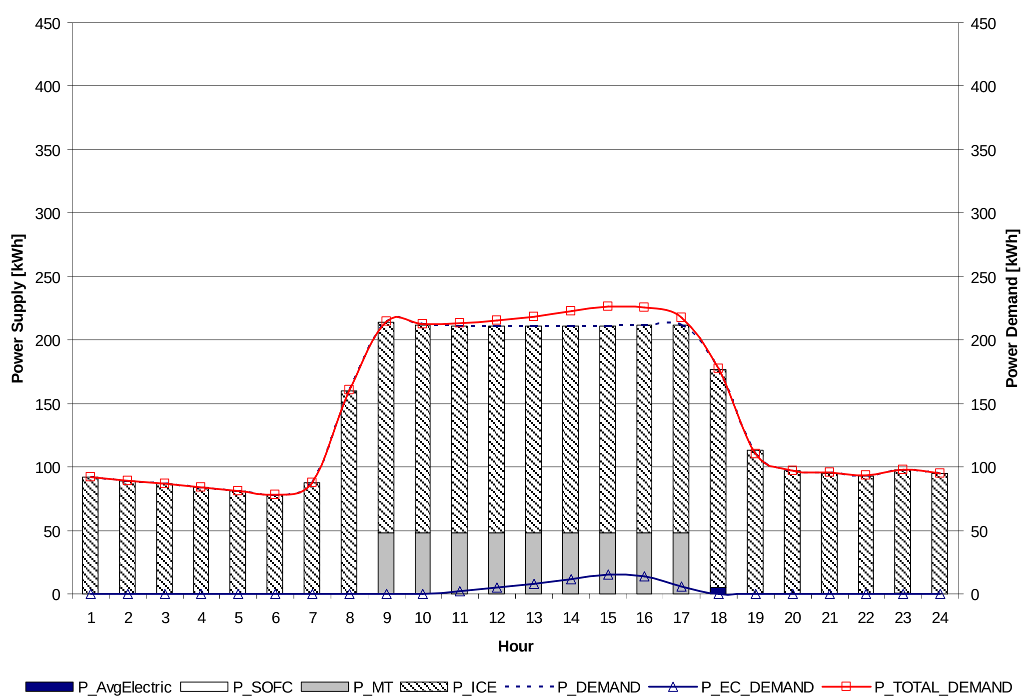



**Figure 6-10: Power supply in an average day in January for min GWP (one ICE).**

APPENDIX E

RESULTS

# E.1 AVERAGE ELECTRIC GRID OPTION: MIN GWP

## E.1.1 *Hourly LCA Optimization Model* for min GWP in an average day in January

**Table 6-11: Supply from the energy systems in an average day in January (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 242 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 259 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 273 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 289 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 306 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 321 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 286 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 145 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33 |
| 10 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 146 |
| 11 | 0 | 0 | 0 | 0 | 9 | 8 | 0 | 212 |
| 12 | 0 | 0 | 0 | 0 | 22 | 21 | 0 | 229 |
| 13 | 0 | 0 | 0 | 0 | 35 | 34 | 0 | 235 |
| 14 | 0 | 0 | 0 | 0 | 54 | 51 | 0 | 230 |
| 15 | 0 | 0 | 0 | 0 | 70 | 67 | 0 | 207 |
| 16 | 0 | 0 | 0 | 0 | 63 | 60 | 0 | 189 |
| 17 | 0 | 0 | 0 | 0 | 28 | 27 | 0 | 172 |
| 18 | 5 | 0 | 0 | 0 | 2 | 1 | 0 | 21 |
| 19 | 0 | 52 | 0 | 0 | 0 | 0 | 3 | 0 |
| 20 | 0 | 110 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 1 | 209 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6-11 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 0 | 231 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |
| 15 | [100%] | 48 | 96 |
| 16 | [100%] | 48 | 96 |
| 17 | [100%] | 48 | 96 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 92 | 210 |
| 2 | [50%] | 89 | 203 |
| 3 | [50%] | 87 | 199 |
| 4 | [50%] | 84 | 192 |
| 5 | [50%] | 81 | 185 |
| 6 | [50%] | 78 | 178 |
| 7 | [50%] | 88 | 201 |
| 8 | [50%] | 80 (unit 1)<br>80 (unit 2) | 183 (unit 1)<br>183 (unit 2) |
| 9 | [100%] | 166 | 273 |
| 10 | [100%] | 164 | 269 |
| 11 | [100%] | 163 | 268 |
| 12 | [100%] | 163 | 268 |
| 13 | [100%] | 163 | 268 |
| 14 | [100%] | 163 | 268 |
| 15 | [100%] | 163 | 268 |
| 16 | [100%] | 164 | 269 |
| 17 | [100%] | 164 | 269 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 97 | 221 |
| 21 | [50%] | 95 | 217 |
| 22 | [50%] | 93 | 212 |
| 23 | [50%] | 97 | 221 |
| 24 | [50%] | 95 | 217 |

### E.1.2 *Hourly LCA Optimization Model* for min GWP in a day in February

**Table 6-12: Supply from the energy systems in an average day in February (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 177 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 214 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 232 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 248 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 263 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 229 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 133 |
| 10 | 0 | 0 | 0 | 0 | 21 | 20 | 0 | 210 |
| 11 | 0 | 0 | 0 | 0 | 41 | 39 | 0 | 232 |
| 12 | 0 | 0 | 0 | 0 | 64 | 61 | 0 | 236 |
| 13 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 234 |
| 14 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 226 |
| 15 | 0 | 0 | 0 | 0 | 121 | 116 | 0 | 197 |
| 16 | 0 | 0 | 0 | 0 | 120 | 114 | 0 | 184 |
| 17 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 191 |
| 18 | 4 | 0 | 0 | 0 | 27 | 26 | 0 | 130 |
| 19 | 0 | 0 | 0 | 0 | 1 | 1 | 8 | 71 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 |
| 21 | 0 | 39 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 118 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 127 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Hour** | **Part Load** | | **P_MT** | | | | **H_MT** | |
| 9 | [100%] | | 48 | | | | 96 | |
| 10 | [100%] | | 48 | | | | 96 | |
| 11 | [100%] | | 48 | | | | 96 | |
| 12 | [100%] | | 48 | | | | 96 | |
| 13 | [100%] | | 48 | | | | 96 | |
| 14 | [100%] | | 48 | | | | 96 | |
| 15 | [100%] | | 48 | | | | 96 | |
| 16 | [100%] | | 48 | | | | 96 | |
| 17 | [100%] | | 48 | | | | 96 | |
| **Hour** | **Part Load** | | **P_ICE** | | | | **H_ICE** | |
| 1 | [50%] | | 89 | | | | 203 | |
| 2 | [50%] | | 86 | | | | 196 | |
| 3 | [50%] | | 83 | | | | 189 | |
| 4 | [50%] | | 80 | | | | 183 | |

| Table 6-12 (continued) | | | |
|---|---|---|---|
| 5 | [50%] | 78 | 178 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 79 (unit 1)<br>79 (unit 2) | 179 (unit 1)<br>179 (unit 2) |
| 9 | [100%] | 164 | 269 |
| 10 | [100%] | 164 | 269 |
| 11 | [100%] | 164 | 269 |
| 12 | [100%] | 164 | 269 |
| 13 | [100%] | 164 | 269 |
| 14 | [100%] | 164 | 269 |
| 15 | [100%] | 164 | 269 |
| 16 | [100%] | 164 | 269 |
| 17 | [100%] | 164 | 269 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 91 | 208 |
| 21 | [50%] | 89 | 203 |
| 22 | [50%] | 88 | 201 |
| 23 | [50%] | 93 | 212 |
| 24 | [50%] | 91 | 208 |

### E.1.3 *Hourly LCA Optimization Model* for min GWP in a day in March

**Table 6-13: Supply from the energy systems in an average day in March (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 54 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 74 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 92 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 109 | 0 | 0 | 0 | 0 | 2 | 0 |
| 5 | 0 | 118 | 0 | 0 | 0 | 0 | 5 | 0 |
| 6 | 0 | 142 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 99 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 13 |
| 9 | 0 | 0 | 0 | 0 | 35 | 33 | 0 | 204 |
| 10 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 202 |
| 11 | 0 | 0 | 0 | 0 | 131 | 124 | 0 | 184 |
| 12 | 0 | 0 | 0 | 0 | 156 | 149 | 0 | 170 |
| 13 | 0 | 0 | 0 | 0 | 178 | 170 | 0 | 159 |
| 14 | 0 | 0 | 0 | 0 | 209 | 199 | 0 | 135 |
| 15 | 0 | 0 | 0 | 0 | 222 | 211 | 0 | 120 |
| 16 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 112 |
| 17 | 0 | 0 | 0 | 0 | 180 | 171 | 0 | 142 |
| 18 | 4 | 0 | 0 | 0 | 102 | 97 | 0 | 112 |

Table 6-13 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 19 | 0 | 0 | 0 | 0 | 25 | 24 | 9 | 123 |
| 20 | 32 | 0 | 0 | 0 | 8 | 7 | 0 | 5 |
| 21 | 0 | 0 | 0 | 0 | 3 | 3 | 0 | 56 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 9 |
| 23 | 0 | 7 | 0 | 1 | 0 | 0 | 0 | 0 |
| 24 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Hour** | **Part Load** | | | **P_MT** | | | **H_MT** | |
| 6 | [75%] | | | 34 (unit 1)<br>34 (unit 2) | | | 79 (unit 1)<br>79 (unit 2) | |
| 9 | [100%] | | | 48 | | | 96 | |
| 10 | [100%] | | | 48 | | | 96 | |
| 11 | [100%] | | | 48 | | | 96 | |
| 12 | [100%] | | | 48 | | | 96 | |
| 13 | [100%] | | | 48 | | | 96 | |
| 14 | [100%] | | | 48 | | | 96 | |
| 15 | [100%] | | | 48 | | | 96 | |
| 16 | [100%] | | | 48 | | | 96 | |
| 17 | [100%] | | | 48 | | | 96 | |
| 20 | [100%] | | | 55 | | | 109 | |
| **Hour** | **Part Load** | | | **P_ICE** | | | **H_ICE** | |
| 1 | [50%] | | | 82 | | | 187 | |
| 2 | [50%] | | | 79 | | | 180 | |
| 3 | [50%] | | | 77 | | | 176 | |
| 4 | [50%] | | | 76 | | | 174 | |
| 5 | [50%] | | | 76 | | | 174 | |
| 7 | [50%] | | | 77 | | | 176 | |
| 8 | [100%] | | | 154 | | | 253 | |
| 9 | [100%] | | | 163 | | | 268 | |
| 10 | [100%] | | | 164 | | | 269 | |
| 11 | [100%] | | | 165 | | | 271 | |
| 12 | [100%] | | | 166 | | | 273 | |
| 13 | [100%] | | | 166 | | | 273 | |
| 14 | [100%] | | | 167 | | | 274 | |
| 15 | [100%] | | | 167 | | | 274 | |
| 16 | [100%] | | | 167 | | | 274 | |
| 17 | [100%] | | | 166 | | | 273 | |
| 18 | [100%] | | | 172 | | | 282 | |
| 19 | [75%] | | | 113 | | | 215 | |
| 21 | [50%] | | | 85 | | | 194 | |
| 22 | [50%] | | | 83 | | | 189 | |
| 23 | [50%] | | | 87 | | | 199 | |
| 24 | [50%] | | | 85 | | | 194 | |

### E.1.4 *Hourly LCA Optimization Model* for min GWP in a day in April

**Table 6-14: Supply from the energy systems in an average day in April (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 19 | 0 | 0 | 0 | 0 | 0 | 0 | 56 |
| 2 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 45 |
| 3 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 28 |
| 4 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 13 |
| 5 | 8 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 5 | 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 180 |
| 9 | 0 | 0 | 0 | 0 | 45 | 43 | 0 | 304 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 0 | 242 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 0 | 182 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 0 | 133 |
| 13 | 0 | 0 | 0 | 0 | 274 | 261 | 0 | 109 |
| 14 | 0 | 0 | 0 | 0 | 314 | 299 | 0 | 71 |
| 15 | 0 | 0 | 0 | 0 | 341 | 325 | 0 | 47 |
| 16 | 0 | 0 | 0 | 0 | 352 | 335 | 0 | 36 |
| 17 | 0 | 0 | 0 | 0 | 334 | 318 | 0 | 51 |
| 18 | 13 | 0 | 0 | 0 | 271 | 258 | 0 | 7 |
| 19 | 0 | 0 | 0 | 0 | 153 | 146 | 0 | 54 |
| 20 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 133 |
| 21 | 27 | 0 | 0 | 0 | 16 | 16 | 0 | 78 |
| 22 | 21 | 0 | 0 | 0 | 4 | 4 | 0 | 85 |
| 23 | 24 | 0 | 0 | 0 | 1 | 1 | 0 | 84 |
| 24 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 49 | 98 |
| 11 | [100%] | 50 | 100 |
| 12 | [100%] | 51 | 102 |
| 13 | [100%] | 52 | 104 |
| 14 | [100%] | 52 | 104 |
| 15 | [100%] | 53 | 106 |
| 16 | [100%] | 53 | 106 |
| 17 | [100%] | 52 | 104 |

| Table 6-14 (continued) | | | |
|---|---|---|---|
| 21 | [100%] | 55 | 109 |
| 22 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 7 | [50%] | 77 | 176 |
| 8 | [100%] | 160 | 263 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 90 | 205 |

### E.1.5 Hourly LCA Optimization Model for min GWP in a day in May

**Table 6-15: Supply from the energy systems in an average day in May (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 17 | 0 | 0 | 0 | 7 | 7 | 0 | 93 |
| 2 | 14 | 0 | 0 | 0 | 5 | 5 | 0 | 92 |
| 3 | 11 | 0 | 0 | 0 | 3 | 3 | 0 | 90 |
| 4 | 8 | 0 | 0 | 0 | 1 | 1 | 0 | 87 |
| 5 | 4 | 0 | 0 | 0 | 1 | 1 | 0 | 83 |
| 6 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 77 |
| 7 | 12 | 0 | 0 | 0 | 7 | 7 | 0 | 82 |
| 8 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 177 |
| 9 | 0 | 0 | 0 | 0 | 163 | 155 | 0 | 204 |
| 10 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 118 |
| 11 | 0 | 0 | 0 | 0 | 329 | 314 | 0 | 48 |
| 12 | 0 | 0 | 0 | 0 | 369 | 352 | 0 | 11 |
| 13 | 0 | 0 | 1 | 4 | 384 | 366 | 0 | 0 |
| 14 | 0 | 0 | 4 | 17 | 392 | 374 | 0 | 0 |
| 15 | 3 | 0 | 8 | 35 | 395 | 376 | 0 | 0 |
| 16 | 0 | 0 | 5 | 23 | 420 | 400 | 0 | 5 |
| 17 | 0 | 0 | 5 | 24 | 392 | 373 | 0 | 0 |
| 18 | 0 | 0 | 6 | 26 | 335 | 319 | 0 | 0 |

Table 6-15 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 19 | 0 | 0 | 6 | 29 | 237 | 226 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 147 | 140 | 0 | 64 |
| 21 | 28 | 0 | 0 | 0 | 55 | 52 | 0 | 51 |
| 22 | 22 | 0 | 0 | 0 | 23 | 22 | 0 | 81 |
| 23 | 24 | 0 | 0 | 0 | 15 | 14 | 0 | 89 |
| 24 | 21 | 0 | 0 | 0 | 10 | 10 | 0 | 94 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 49 | 98 |
| 13 | [100%] | 50 | 100 |
| 14 | [100%] | 54 | 107 |
| 15 | [100%] | 55 | 109 |
| 17 | [100%] | 54 | 108 |
| 18 | [75%] | 34 | 79 |
| 21 | [100%] | 55 | 109 |
| 22 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 8 | [100%] | 157 | 258 |
| 9 | [100%] | 170 | 279 |
| 10 | [100%] | 171 | 281 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 151 [100%] (unit 1)<br>76 [50%] (unit 2) | 248 [100%] (unit 1)<br>174 [50%] (unit 2) |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 155 | 254 |
| 19 | [75%] | 124 | 258 |
| 20 | [50%] | 93 | 212 |

### E.1.6 Hourly LCA Optimization Model for min GWP in a day in June

**Table 6-16: Supply from the energy systems in an average day in June (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 18 | 0 | 0 | 0 | 26 | 25 | 0 | 78 |
| 2 | 15 | 0 | 0 | 0 | 22 | 21 | 0 | 82 |
| 3 | 11 | 0 | 0 | 0 | 19 | 18 | 0 | 86 |
| 4 | 8 | 0 | 0 | 0 | 15 | 14 | 0 | 89 |
| 5 | 4 | 0 | 0 | 0 | 11 | 11 | 0 | 92 |
| 6 | 1 | 0 | 0 | 0 | 9 | 9 | 0 | 93 |
| 7 | 13 | 0 | 0 | 0 | 44 | 42 | 0 | 61 |
| 8 | 0 | 0 | 0 | 0 | 184 | 175 | 0 | 60 |
| 9 | 0 | 0 | 0 | 0 | 304 | 289 | 0 | 59 |
| 10 | 0 | 0 | 4 | 19 | 376 | 358 | 0 | 0 |
| 11 | 3 | 0 | 16 | 74 | 396 | 377 | 0 | 0 |
| 12 | 0 | 0 | 16 | 75 | 432 | 411 | 0 | 0 |
| 13 | 0 | 0 | 18 | 81 | 436 | 416 | 0 | 0 |
| 14 | 0 | 0 | 21 | 94 | 442 | 421 | 0 | 0 |
| 15 | 0 | 0 | 22 | 103 | 445 | 424 | 0 | 0 |
| 16 | 0 | 0 | 27 | 122 | 452 | 430 | 0 | 0 |
| 17 | 0 | 0 | 25 | 114 | 449 | 427 | 0 | 0 |
| 18 | 0 | 0 | 28 | 127 | 368 | 350 | 0 | 0 |
| 19 | 0 | 0 | 34 | 156 | 255 | 243 | 0 | 0 |
| 20 | 0 | 0 | 16 | 73 | 191 | 182 | 0 | 25 |
| 21 | 0 | 0 | 0 | 0 | 124 | 118 | 0 | 72 |
| 22 | 24 | 0 | 0 | 0 | 64 | 61 | 0 | 42 |
| 23 | 26 | 0 | 0 | 0 | 44 | 42 | 0 | 61 |
| 24 | 22 | 0 | 0 | 0 | 34 | 32 | 0 | 71 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 55 | 109 |
| 18 | [75%] | 35 | 81 |
| 22 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |

| P_ICE |
|---|
| |

Table 6-16 (continued)

| **Hour** | **Part Load** | **1** | **2** |
|---|---|---|---|
| 8 | [100%] | 153 | 0 |
| 9 | [100%] | 163 | 0 |
| 10 | [100%] | 169 | 0 |
| 11 | [100%] | 172 | 0 |
| 12 | [100%], [50%] | 155 | 76 [50%] |
| 13 | [100%], [50%] | 157 | 76 [50%] |
| 14 | [100%], [50%] | 160 | 76 [50%] |
| 15 | [100%], [50%] | 161 | 76 [50%] |
| 16 | [100%], [50%] | 167 | 76 [50%] |
| 17 | [100%], [50%] | 165 | 76 [50%] |
| 18 | [100%] | 172 | 0 |
| 19 | [100%] | 154 | 0 |
| 20 | [75%] | 113 | 0 |
| 21 | [50%] | 86 | - |

**H_ICE**

| **Hour** | **Part Load** | **Unit 1** | **Unit 2** |
|---|---|---|---|
| 8 | [100%] | 251 | 0 |
| 9 | [100%] | 268 | 0 |
| 10 | [100%] | 278 | 0 |
| 11 | [100%] | 282 | 0 |
| 12 | [100%], [50%] | 255 | 174 [50%] |
| 13 | [100%], [50%] | 257 | 174 [50%] |
| 14 | [100%], [50%] | 262 | 174 [50%] |
| 15 | [100%], [50%] | 265 | 174 [50%] |
| 16 | [100%], [50%] | 274 | 174 [50%] |
| 17 | [100%], [50%] | 271 | 174 [50%] |
| 18 | [100%] | 282 | 0 |
| 19 | [100%] | 253 | 0 |
| 20 | [75%] | 215 | 0 |
| 21 | [50%] | 196 | 0 |

## E.1.7 *Hourly LCA Optimization Model* for min GWP in a day in July

**Table 6-17: Supply from the energy systems in an average day in July (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 20 | 0 | 0 | 0 | 60 | 57 | 0 | 46 |
| 2 | 16 | 0 | 0 | 0 | 52 | 50 | 0 | 54 |
| 3 | 13 | 0 | 0 | 0 | 45 | 43 | 0 | 60 |
| 4 | 9 | 0 | 0 | 0 | 38 | 36 | 0 | 67 |
| 5 | 5 | 0 | 0 | 0 | 31 | 30 | 0 | 74 |
| 6 | 2 | 0 | 0 | 0 | 27 | 26 | 0 | 77 |
| 7 | 14 | 0 | 0 | 0 | 64 | 61 | 0 | 42 |
| 8 | 0 | 0 | 0 | 0 | 236 | 225 | 0 | 20 |
| 9 | 0 | 0 | 0 | 0 | 372 | 354 | 0 | 8 |
| 10 | 0 | 0 | 11 | 49 | 434 | 413 | 0 | 0 |
| 11 | 0 | 0 | 25 | 113 | 462 | 440 | 0 | 0 |
| 12 | 0 | 0 | 41 | 188 | 460 | 438 | 0 | 8 |
| 13 | 0 | 0 | 45 | 207 | 476 | 454 | 0 | 0 |
| 14 | 0 | 0 | 48 | 218 | 480 | 457 | 0 | 0 |
| 15 | 0 | 0 | 52 | 240 | 489 | 466 | 0 | 0 |
| 16 | 0 | 0 | 58 | 264 | 498 | 475 | 0 | 0 |
| 17 | 0 | 0 | 57 | 260 | 497 | 473 | 0 | 0 |
| 18 | 0 | 0 | 49 | 223 | 441 | 420 | 0 | 0 |
| 19 | 14 | 0 | 58 | 267 | 285 | 271 | 0 | 0 |
| 20 | 0 | 0 | 25 | 113 | 245 | 233 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 192 | 183 | 0 | 16 |
| 22 | 0 | 0 | 0 | 0 | 119 | 114 | 0 | 68 |
| 23 | 28 | 0 | 0 | 0 | 91 | 87 | 0 | 17 |
| 24 | 24 | 0 | 0 | 0 | 74 | 70 | 0 | 33 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |

**P_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 8 | [100%] | 159 | 0 |

| Table 6-17 (continued) | | | |
|---|---|---|---|
| 9 | [100%] | 172 | 0 |
| 10 | [100%], [50%] | 156 | 76 [50%] |
| 11 | [100%], [50%] | 172 | 76 [50%] |
| 12 | [100%], [75%] | 151 | 113 [75%] |
| 13 | [100%], [75%] | 155 | 113 [75%] |
| 14 | [100%], [75%] | 158 | 113 [75%] |
| 15 | [100%], [75%] | 162 | 113 [75%] |
| 16 | [100%], [75%] | 169 | 113 [75%] |
| 17 | [100%], [75%] | 168 | 113 [75%] |
| 18 | [100%], [50%] | 159 | 76 [50%] |
| 19 | [100%] | 172 | 0 |
| 20 | [75%] | 127 | 0 |
| 21 | [50%] | 90 | - |
| 22 | [50%] | 82 | - |

**H_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 8 | [100%] | 261 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 256 | 174 [50%] |
| 11 | [100%] | 282 | 174 [50%] |
| 12 | [100%], [75%] | 248 | 215 [75%] |
| 13 | [100%], [75%] | 255 | 215 [75%] |
| 14 | [100%], [75%] | 259 | 215 [75%] |
| 15 | [100%], [75%] | 267 | 215 [75%] |
| 16 | [100%], [75%] | 277 | 215 [75%] |
| 17 | [100%], [75%] | 275 | 215 [75%] |
| 18 | [100%] | 260 | 174 [50%] |
| 19 | [100%] | 282 | 0 |
| 20 | [75%] | 241 | 0 |
| 21 | [50%] | 205 | - |
| 22 | [50%] | 187 | - |

### E.1.8 *Hourly LCA Optimization Model* for min GWP in a day in August

**Table 6-18: Supply from the energy systems in an average day in August (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 19 | 0 | 0 | 0 | 49 | 47 | 0 | 57 |
| 2 | 16 | 0 | 0 | 0 | 40 | 38 | 0 | 65 |
| 3 | 12 | 0 | 0 | 0 | 34 | 32 | 0 | 71 |
| 4 | 9 | 0 | 0 | 0 | 29 | 27 | 0 | 76 |
| 5 | 5 | 0 | 0 | 0 | 25 | 23 | 0 | 80 |
| 6 | 2 | 0 | 0 | 0 | 22 | 21 | 0 | 83 |

Table 6-18 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7 | 13 | 0 | 0 | 0 | 33 | 32 | 0 | 72 |
| 8 | 0 | 0 | 0 | 0 | 189 | 180 | 0 | 62 |
| 9 | 0 | 0 | 0 | 0 | 343 | 326 | 0 | 36 |
| 10 | 0 | 0 | 7 | 31 | 429 | 408 | 0 | 0 |
| 11 | 0 | 0 | 23 | 108 | 459 | 437 | 0 | 0 |
| 12 | 0 | 0 | 40 | 183 | 443 | 422 | 0 | 24 |
| 13 | 0 | 0 | 40 | 183 | 468 | 446 | 0 | 1 |
| 14 | 0 | 0 | 44 | 200 | 474 | 451 | 0 | 0 |
| 15 | 0 | 0 | 48 | 220 | 483 | 460 | 0 | 0 |
| 16 | 0 | 0 | 52 | 239 | 489 | 466 | 0 | 0 |
| 17 | 0 | 0 | 49 | 224 | 483 | 460 | 0 | 0 |
| 18 | 0 | 0 | 42 | 192 | 397 | 378 | 0 | 0 |
| 19 | 0 | 0 | 40 | 182 | 271 | 258 | 0 | 0 |
| 20 | 0 | 0 | 16 | 73 | 181 | 172 | 0 | 35 |
| 21 | 0 | 0 | 0 | 0 | 132 | 126 | 0 | 67 |
| 22 | 25 | 0 | 0 | 0 | 84 | 80 | 0 | 23 |
| 23 | 27 | 0 | 0 | 0 | 65 | 62 | 0 | 41 |
| 24 | 23 | 0 | 0 | 0 | 55 | 53 | 0 | 51 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |
| 18 | [100%] | 55 | 109 |
| 22 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |

**P_ICE**

| **Hour** | **Part Load** | **Unit 1** | **Unit 2** |
|---|---|---|---|
| 8 | [100%] | 158 | 0 |
| 9 | [100%] | 172 | 0 |
| 10 | [100%], [50%] | 153 | 76 [50%] |
| 11 | [100%], [50%] | 170 | 76 [50%] |
| 12 | [100%], [75%] | 151 | 113 [75%] |
| 13 | [100%], [75%] | 151 | 113 [75%] |
| 14 | [100%], [75%] | 154 | 113 [75%] |
| 15 | [100%], [75%] | 159 | 113 [75%] |
| 16 | [100%], [75%] | 163 | 113 [75%] |
| 17 | [100%], [75%] | 160 | 113 [75%] |
| 18 | [100%], [50%] | 172 | 76 [50%] |

| Table 6-18 (continued) | | | |
|---|---|---|---|
| 19 | [100%] | 164 | 0 |
| 20 | [75%] | 113 | 0 |
| 21 | [50%] | 87 | 0 |

**H_ICE**

| **Hour** | **Part Load** | **Unit 1** | **Unit 2** |
|---|---|---|---|
| 8 | [100%] | 259 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 251 | 174 [50%] |
| 11 | [100%] | 280 | 174 [50%] |
| 12 | [100%], [75%] | 248 | 215 [75%] |
| 13 | [100%], [75%] | 248 | 215 [75%] |
| 14 | [100%], [75%] | 252 | 215 [75%] |
| 15 | [100%], [75%] | 261 | 215 [75%] |
| 16 | [100%], [75%] | 268 | 215 [75%] |
| 17 | [100%], [75%] | 263 | 215 [75%] |
| 18 | [100%] | 282 | 174 [50%] |
| 19 | [100%] | 269 | 0 |
| 20 | [75%] | 215 | 0 |
| 21 | [50%] | 205 | - |
| 22 | [50%] | 199 | - |

### E.1.9 *Hourly LCA Optimization Model* for min GWP in a day in September

**Table 6-19: Supply from the energy systems in an average day in September (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 18 | 0 | 0 | 0 | 16 | 15 | 0 | 88 |
| 2 | 14 | 0 | 0 | 0 | 12 | 12 | 0 | 92 |
| 3 | 11 | 0 | 0 | 0 | 10 | 9 | 0 | 93 |
| 4 | 8 | 0 | 0 | 0 | 7 | 7 | 0 | 93 |
| 5 | 4 | 0 | 0 | 0 | 6 | 5 | 0 | 92 |
| 6 | 1 | 0 | 0 | 0 | 4 | 4 | 0 | 90 |
| 7 | 11 | 0 | 0 | 0 | 8 | 7 | 0 | 84 |
| 8 | 0 | 0 | 0 | 0 | 79 | 75 | 0 | 155 |
| 9 | 0 | 0 | 0 | 0 | 173 | 165 | 0 | 182 |
| 10 | 0 | 0 | 0 | 0 | 284 | 271 | 0 | 81 |
| 11 | 0 | 0 | 1 | 6 | 373 | 355 | 0 | 0 |
| 12 | 0 | 0 | 9 | 42 | 388 | 369 | 0 | 0 |
| 13 | 5 | 0 | 16 | 72 | 396 | 377 | 0 | 0 |
| 14 | 0 | 0 | 14 | 62 | 431 | 411 | 0 | 0 |
| 15 | 0 | 0 | 18 | 84 | 439 | 418 | 0 | 0 |
| 16 | 0 | 0 | 22 | 99 | 443 | 422 | 0 | 0 |
| 17 | 0 | 0 | 16 | 71 | 433 | 412 | 0 | 0 |

Table 6-19 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 18 | 0 | 0 | 11 | 52 | 337 | 321 | 0 | 0 |
| 19 | 0 | 0 | 6 | 28 | 229 | 218 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 122 | 116 | 0 | 81 |
| 21 | 28 | 0 | 0 | 0 | 65 | 62 | 0 | 41 |
| 22 | 22 | 0 | 0 | 0 | 36 | 34 | 0 | 69 |
| 23 | 25 | 0 | 0 | 0 | 25 | 24 | 0 | 79 |
| 24 | 21 | 0 | 0 | 0 | 20 | 19 | 0 | 84 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 52 | 104 |
| 13 | [100%] | 55 | 109 |
| 18 | [75%] | 34 | 79 |
| 21 | [100%] | 55 | 109 |
| 22 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |

**P_ICE**

| **Hour** | **Part Load** | **Unit q1** | **Unit 2** |
|---|---|---|---|
| 8 | [100%] | 152 | 0 |
| 9 | [100%] | 162 | 0 |
| 10 | [100%] | 165 | 0 |
| 11 | [100%] | 167 | 0 |
| 12 | [100%] | 172 | 0 |
| 13 | [100%] | 172 | 0 |
| 14 | [100%], [50%] | 154 | 76 [50%] |
| 15 | [100%], [50%] | 158 | 76 [50%] |
| 16 | [100%], [50%] | 162 | 76 [50%] |
| 17 | [100%], [50%] | 156 | 76 [50%] |
| 18 | [100%] | 155 | 0 |
| 19 | [75%] | 120 | 0 |
| 20 | [50%] | 76 | 0 |

**H_ICE**

| **Hour** | **Part Load** | **Unit 1** | **Unit 2** |
|---|---|---|---|
| 8 | [100%] | 250 | 0 |

| Table 6-19 (continued) | | | |
|---|---|---|---|
| 9 | [100%] | 266 | 0 |
| 10 | [100%] | 271 | 0 |
| 11 | [100%] | 275 | 0 |
| 12 | [100%] | 282 | 0 |
| 13 | [100%] | 282 | 0 |
| 14 | [100%], [50%] | 252 | 174 [50%] |
| 15 | [100%], [50%] | 260 | 174 [50%] |
| 16 | [100%], [50%] | 265 | 174 [50%] |
| 17 | [100%], [50%] | 255 | 174 [50%] |
| 18 | [100%] | 255 | 0 |
| 19 | [75%] | 228 | 0 |
| 20 | [50%] | 205 | 0 |

### E.1.10 *Hourly LCA Optimization Model* for min GWP in a day in October

**Table 6-20: Supply from the energy systems in an average day in October (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 19 | 0 | 0.00 | 0.00 | 0.17 | 0.16 | 0 | 54 |
| 2 | 16 | 0 | 0.00 | 0.00 | 0.18 | 0.17 | 0 | 41 |
| 3 | 13 | 0 | 0.00 | 0.00 | 0.26 | 0.25 | 0 | 26 |
| 4 | 11 | 0 | 0.00 | 0.00 | 0.07 | 0.07 | 0 | 13 |
| 5 | 8 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 0 |
| 6 | 5 | 14 | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 0 |
| 7 | 3 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 34 |
| 8 | 0 | 0 | 0.00 | 0.00 | 2.57 | 2.45 | 0 | 143 |
| 9 | 0 | 0 | 0.00 | 0.00 | 24.44 | 23.28 | 0 | 318 |
| 10 | 0 | 0 | 0.00 | 0.00 | 106.89 | 101.80 | 0 | 254 |
| 11 | 0 | 0 | 0.00 | 0.00 | 208.19 | 198.28 | 0 | 159 |
| 12 | 0 | 0 | 0.00 | 0.00 | 279.93 | 266.60 | 0 | 93 |
| 13 | 0 | 0 | 0.00 | 0.00 | 320.89 | 305.61 | 0 | 55 |
| 14 | 0 | 0 | 0.00 | 0.00 | 351.37 | 334.64 | 0 | 27 |
| 15 | 0 | 0 | 0.00 | 0.00 | 375.94 | 358.04 | 0 | 6 |
| 16 | 0 | 0 | 0.00 | 0.00 | 372.37 | 354.64 | 0 | 6 |
| 17 | 0 | 0 | 0.00 | 0.00 | 323.67 | 308.26 | 0 | 51 |
| 18 | 9 | 0 | 0.00 | 0.00 | 224.40 | 213.71 | 0 | 55 |
| 19 | 0 | 0 | 0.00 | 0.00 | 70.13 | 66.79 | 6 | 137 |
| 20 | 30 | 0 | 0.00 | 0.00 | 16.33 | 15.55 | 0 | 86 |
| 21 | 25 | 0 | 0.00 | 0.00 | 4.15 | 3.95 | 0 | 98 |
| 22 | 20 | 0 | 0.00 | 0.00 | 1.13 | 1.08 | 0 | 94 |
| 23 | 24 | 0 | 0.00 | 0.00 | 0.42 | 0.40 | 0 | 80 |
| 24 | 22 | 0 | 0.00 | 0.00 | 0.19 | 0.18 | 0 | 65 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 1 | [100%] | 55 | 109 |

| Table 6-20 (continued) | | | |
|---|---|---|---|
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [75%] | 34 (Unit 1)<br>34 (Unit 2) | 79 (unit 1)<br>79 (unit 2) |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |
| 15 | [100%] | 49 | 98 |
| 16 | [100%] | 48 | 96 |
| 17 | [100%] | 48 | 96 |
| 20 | [100%] | 55 | 109 |
| 21 | [100%] | 55 | 109 |
| 22 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [100%] | 55 | 109 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 8 | [100%] | 156 | 256 |
| 9 | [100%] | 167 | 274 |
| 10 | [100%] | 168 | 276 |
| 11 | [100%] | 169 | 278 |
| 12 | [100%] | 171 | 281 |
| 13 | [100%] | 171 | 281 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 171 | 281 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |

### E.1.11 Hourly LCA Optimization Model for min GWP in a day in November

**Table 6-21: Supply from the energy systems in an average day in November (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 46 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 61 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 75 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 83 | 0 | 0 | 0 | 0 | 3 | 0 |
| 5 | 0 | 90 | 0 | 0 | 0 | 0 | 6 | 0 |
| 6 | 0 | 112 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 26 |
| 9 | 32 | 0 | 0 | 0 | 12 | 11 | 0 | 161 |
| 10 | 31 | 0 | 0 | 0 | 40 | 38 | 0 | 189 |
| 11 | 31 | 0 | 0 | 0 | 67 | 63 | 0 | 185 |
| 12 | 32 | 0 | 0 | 0 | 106 | 101 | 0 | 152 |
| 13 | 32 | 0 | 0 | 0 | 137 | 131 | 0 | 124 |
| 14 | 33 | 0 | 0 | 0 | 157 | 149 | 0 | 108 |
| 15 | 33 | 0 | 0 | 0 | 168 | 160 | 0 | 88 |
| 16 | 32 | 0 | 0 | 0 | 141 | 134 | 0 | 102 |
| 17 | 31 | 0 | 0 | 0 | 76 | 73 | 0 | 146 |
| 18 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 178 |
| 19 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 115 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 77 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35 |
| 22 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 |

**P_MT**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 6 | [75%] | 34 | 34 |
| 19 | [100%] | 52 | 48 |

**H_MT**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 6 | [75%] | 79 | 79 |
| 19 | [100%] | 104 | 96 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 76 | 174 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |

| Table 6-21 (continued) | | | |
|---|---|---|---|
| 8 | [100%] | 151 | 248 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 168 | 276 |
| 20 | [50%] | 86 | 196 |
| 21 | [50%] | 85 | 194 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 88 | 201 |
| 24 | [50%] | 85 | 194 |

### E.1.12 *Hourly LCA Optimization Model* for min GWP in a day in December

**Table 6-22: Supply from the energy systems in an average day in December (Hourly model: min GWP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 178 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 194 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 210 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 223 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 235 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 244 | 0 | 0 | 0 | 0 | 2 | 0 |
| 7 | 0 | 217 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 83 |
| 10 | 0 | 0 | 0 | 0 | 5 | 4 | 0 | 174 |
| 11 | 0 | 0 | 0 | 0 | 15 | 15 | 0 | 221 |
| 12 | 0 | 0 | 0 | 0 | 29 | 28 | 0 | 237 |
| 13 | 0 | 0 | 0 | 0 | 57 | 55 | 0 | 220 |
| 14 | 0 | 0 | 0 | 0 | 78 | 75 | 0 | 209 |
| 15 | 0 | 0 | 0 | 0 | 81 | 77 | 0 | 210 |
| 16 | 0 | 0 | 0 | 0 | 52 | 49 | 0 | 222 |
| 17 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 207 |
| 18 | 3 | 0 | 0 | 0 | 6 | 6 | 0 | 77 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 17 |
| 20 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 133 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6-22 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 23 | 0 | 139 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Hour** | **Part Load** | | **P_MT** | | | **H_MT** | | |
| 9 | [100%] | | 48 | | | 96 | | |
| 10 | [100%] | | 48 | | | 96 | | |
| 11 | [100%] | | 48 | | | 96 | | |
| 12 | [100%] | | 48 | | | 96 | | |
| 13 | [100%] | | 48 | | | 96 | | |
| 14 | [100%] | | 48 | | | 96 | | |
| 15 | [100%] | | 48 | | | 96 | | |
| 16 | [100%] | | 48 | | | 96 | | |
| 17 | [100%] | | 48 | | | 96 | | |
| **Hour** | **Part Load** | | **P_ICE** | | | **H_ICE** | | |
| 1 | [50%] | | 89 | | | 203 | | |
| 2 | [50%] | | 86 | | | 196 | | |
| 3 | [50%] | | 83 | | | 189 | | |
| 4 | [50%] | | 80 | | | 183 | | |
| 5 | [50%] | | 77 | | | 176 | | |
| 6 | [50%] | | 76 | | | 174 | | |
| 7 | [50%] | | 84 | | | 192 | | |
| 8 | [50%] | | 79 (unit 1)<br>79 (unit 2) | | | 180 (unit 1)<br>180 (unit 2) | | |
| 9 | [100%] | | 165 | | | 271 | | |
| 10 | [100%] | | 164 | | | 269 | | |
| 11 | [100%] | | 163 | | | 268 | | |
| 12 | [100%] | | 163 | | | 268 | | |
| 13 | [100%] | | 163 | | | 268 | | |
| 14 | [100%] | | 164 | | | 269 | | |
| 15 | [100%] | | 165 | | | 271 | | |
| 16 | [100%] | | 164 | | | 269 | | |
| 17 | [100%] | | 163 | | | 268 | | |
| 18 | [100%] | | 172 | | | 282 | | |
| 19 | [75%] | | 113 | | | 215 | | |
| 20 | [50%] | | 86 | | | 215 | | |
| 21 | [50%] | | 85 | | | 210 | | |
| 22 | [50%] | | 83 | | | 205 | | |
| 23 | [50%] | | 88 | | | 215 | | |
| 24 | [50%] | | 85 | | | 208 | | |

## E.2 AVERAGE ELECTRIC GRID OPTION: MIN $CO_2$

### E.2.1 Hourly LCA Optimization Model for min $CO_2$ in a day in January

**Table 6-23: Supply from the energy systems in an average day in January (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 242 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 259 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 273 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 289 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 306 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 321 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 286 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 145 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33 |
| 10 | 40 | 0 | 0 | 0 | 1 | 1 | 0 | 64 |
| 11 | 39 | 0 | 0 | 0 | 9 | 8 | 0 | 131 |
| 12 | 39 | 0 | 0 | 0 | 22 | 21 | 0 | 148 |
| 13 | 39 | 0 | 0 | 0 | 35 | 34 | 0 | 154 |
| 14 | 39 | 0 | 0 | 0 | 54 | 51 | 0 | 149 |
| 15 | 39 | 0 | 0 | 0 | 70 | 67 | 0 | 127 |
| 16 | 40 | 0 | 0 | 0 | 63 | 60 | 0 | 106 |
| 17 | 40 | 0 | 0 | 0 | 28 | 27 | 0 | 90 |
| 18 | 5 | 0 | 0 | 0 | 2 | 1 | 0 | 21 |
| 19 | 0 | 52 | 0 | 0 | 0 | 0 | 3 | 0 |
| 20 | 0 | 110 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 1 | 209 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 231 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Hour** | **Part Load** | | **P_MT** | | | **H_MT** | | |
| 9 | [100%] | | 48 | | | 96 | | |
| **Hour** | **Part Load** | | **P_ICE** | | | **H_ICE** | | |
| 1 | [50%] | | 92 | | | 210 | | |
| 2 | [50%] | | 89 | | | 203 | | |
| 3 | [50%] | | 87 | | | 199 | | |
| 4 | [50%] | | 84 | | | 192 | | |
| 5 | [50%] | | 81 | | | 185 | | |
| 6 | [50%] | | 78 | | | 178 | | |
| 7 | [50%] | | 88 | | | 201 | | |
| 8 | [50%] | | 80 (unit 1)<br>80 (unit 2) | | | 183 (unit 1)<br>183 (unit 2) | | |
| 9 | [100%] | | 166 | | | 273 | | |

| Table 6-23 (continued) | | | |
|---|---|---|---|
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 97 | 221 |
| 21 | [50%] | 95 | 217 |
| 22 | [50%] | 93 | 212 |
| 23 | [50%] | 97 | 221 |
| 24 | [50%] | 95 | 217 |

### E.2.2 *Hourly LCA Optimization Model* for min $CO_2$ in a day in February

**Table 6-24: Supply from the energy systems in an average day in February (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 177 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 214 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 232 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 248 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 263 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 229 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 50 |
| 10 | 40 | 0 | 0 | 0 | 21 | 20 | 0 | 127 |
| 11 | 40 | 0 | 0 | 0 | 41 | 39 | 0 | 149 |
| 12 | 40 | 0 | 0 | 0 | 64 | 61 | 0 | 153 |
| 13 | 40 | 0 | 0 | 0 | 86 | 82 | 0 | 152 |
| 14 | 40 | 0 | 0 | 0 | 97 | 92 | 0 | 143 |
| 15 | 40 | 0 | 0 | 0 | 121 | 116 | 0 | 115 |
| 16 | 40 | 0 | 0 | 0 | 120 | 114 | 0 | 101 |
| 17 | 40 | 0 | 0 | 0 | 97 | 92 | 0 | 108 |
| 18 | 4 | 0 | 0 | 0 | 27 | 26 | 0 | 130 |
| 19 | 0 | 0 | 0 | 0 | 1 | 1 | 8 | 71 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 |
| 21 | 0 | 39 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 118 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6-24 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 0 | 127 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 78 | 178 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 79 (unit 1)<br>79 (unit 2) | 179 (unit 1)<br>179 (unit 2) |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 91 | 208 |
| 21 | [50%] | 89 | 203 |
| 22 | [50%] | 88 | 201 |
| 23 | [50%] | 93 | 212 |
| 24 | [50%] | 91 | 208 |

### E.2.3 *Hourly LCA Optimization Model* for min $CO_2$ in a day in March

**Table 6-25: Supply from the energy systems in an average day in March (Hourly model: min $CO_2$).**

| **Hour** | **P_GRID** | **H_BOILER** | **P_EC** | **C_EC** | **C_AC** | **H_AC** | **P_EXCESS** | **H_EXCESS** |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 54 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 74 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 92 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 109 | 0 | 0 | 0 | 0 | 2 | 0 |
| 5 | 0 | 118 | 0 | 0 | 0 | 0 | 5 | 0 |
| 6 | 0 | 142 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 99 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 13 |
| 9 | 0 | 0 | 0 | 0 | 35 | 33 | 0 | 204 |
| 10 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 202 |
| 11 | 0 | 0 | 0 | 0 | 131 | 124 | 0 | 184 |

Table 6-25 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12 | 0 | 0 | 0 | 0 | 156 | 149 | 0 | 170 |
| 13 | 0 | 0 | 0 | 0 | 178 | 170 | 0 | 159 |
| 14 | 0 | 0 | 0 | 0 | 209 | 199 | 0 | 135 |
| 15 | 0 | 0 | 0 | 0 | 222 | 211 | 0 | 120 |
| 16 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 112 |
| 17 | 0 | 0 | 0 | 0 | 180 | 171 | 0 | 142 |
| 18 | 4 | 0 | 0 | 0 | 102 | 97 | 0 | 112 |
| 19 | 0 | 0 | 0 | 0 | 25 | 24 | 9 | 123 |
| 20 | 32 | 0 | 0 | 0 | 8 | 7 | 0 | 5 |
| 21 | 0 | 0 | 0 | 0 | 3 | 3 | 0 | 56 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 9 |
| 23 | 0 | 7 | 0 | 1 | 0 | 0 | 0 | 0 |
| 24 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 77 | 176 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 77 | 176 |
| 8 | [100%] | 154 | 253 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 87 | 199 |
| 21 | [50%] | 85 | 194 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 87 | 199 |
| 24 | [50%] | 85 | 194 |

### E.2.4 *Hourly LCA Optimization Model* for min $CO_2$ in a day in April

**Table 6-26: Supply from the energy systems in an average day in April (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 121 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 110 |
| 3 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 28 |
| 4 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 13 |
| 5 | 8 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 5 | 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 65 |
| 8 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 180 |
| 9 | 0 | 0 | 0 | 0 | 45 | 43 | 0 | 304 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 0 | 242 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 0 | 182 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 0 | 133 |
| 13 | 0 | 0 | 0 | 0 | 274 | 261 | 0 | 109 |
| 14 | 0 | 0 | 0 | 0 | 314 | 299 | 0 | 71 |
| 15 | 0 | 0 | 0 | 0 | 341 | 325 | 0 | 47 |
| 16 | 0 | 0 | 0 | 0 | 352 | 335 | 0 | 36 |
| 17 | 0 | 0 | 0 | 0 | 334 | 318 | 0 | 51 |
| 18 | 13 | 0 | 0 | 0 | 271 | 258 | 0 | 7 |
| 19 | 0 | 0 | 0 | 0 | 153 | 146 | 0 | 54 |
| 20 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 133 |
| 21 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 156 |
| 22 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 149 |
| 23 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 155 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 123 |
| **Hour** | **Part Load** | | **P_MT** | | | **H_MT** | | |
| 3 | [100%] | | 55 | | | 109 | | |
| 4 | [100%] | | 55 | | | 109 | | |
| 5 | [100%] | | 55 | | | 109 | | |
| 6 | [100%] | | 55 | | | 109 | | |
| 9 | [100%] | | 48 | | | 96 | | |
| 10 | [100%] | | 49 | | | 98 | | |
| 11 | [100%] | | 50 | | | 100 | | |
| 12 | [100%] | | 51 | | | 102 | | |
| 13 | [100%] | | 52 | | | 104 | | |
| 14 | [100%] | | 52 | | | 104 | | |
| 15 | [100%] | | 53 | | | 106 | | |
| 16 | [100%] | | 53 | | | 106 | | |
| 17 | [100%] | | 52 | | | 104 | | |
| **Hour** | **Part Load** | | **P_ICE** | | | **H_ICE** | | |
| 1 | [50%] | | 76 | | | 174 | | |

| Table 6-26 (continued) | | | |
|---|---|---|---|
| 2 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |
| 8 | [100%] | 160 | 263 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 90 | 205 |
| 21 | [50%] | 82 | 187 |
| 22 | [50%] | 76 | 174 |
| 23 | [50%] | 79 | 180 |
| 24 | [50%] | 77 | 176 |

### E.2.5 *Hourly LCA Optimization Model* for min $CO_2$ in a day in May

**Table 6-27: Supply from the energy systems in an average day in May (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 7 | 7 | 4 | 157 |
| 2 | 14 | 0 | 0 | 0 | 5 | 5 | 0 | 92 |
| 3 | 11 | 0 | 0 | 0 | 3 | 3 | 0 | 90 |
| 4 | 8 | 0 | 0 | 0 | 1 | 1 | 0 | 87 |
| 5 | 4 | 0 | 0 | 0 | 1 | 1 | 0 | 83 |
| 6 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 77 |
| 7 | 12 | 0 | 0 | 0 | 7 | 7 | 0 | 82 |
| 8 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 177 |
| 9 | 46 | 0 | 0 | 0 | 163 | 155 | 0 | 111 |
| 10 | 47 | 0 | 0 | 0 | 255 | 243 | 0 | 24 |
| 11 | 0 | 0 | 0 | 0 | 329 | 314 | 0 | 48 |
| 12 | 0 | 0 | 0 | 0 | 369 | 352 | 0 | 11 |
| 13 | 0 | 0 | 1 | 4 | 384 | 366 | 0 | 0 |
| 14 | 0 | 0 | 4 | 17 | 392 | 374 | 0 | 0 |
| 15 | 0 | 0 | 5 | 23 | 407 | 387 | 0 | 18 |
| 16 | 0 | 0 | 5 | 23 | 420 | 400 | 0 | 5 |
| 17 | 0 | 0 | 5 | 24 | 392 | 373 | 0 | 0 |
| 18 | 0 | 0 | 5 | 25 | 336 | 320 | 0 | 0 |
| 19 | 0 | 0 | 6 | 29 | 237 | 226 | 0 | 0 |

Table 6-27 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 20 | 0 | 0 | 0 | 0 | 147 | 140 | 0 | 64 |
| 21 | 0 | 0 | 0 | 0 | 55 | 52 | 0 | 132 |
| 22 | 0 | 0 | 0 | 0 | 23 | 22 | 0 | 148 |
| 23 | 0 | 0 | 0 | 0 | 15 | 14 | 0 | 160 |
| 24 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 158 |
| Hour | Part Load | | P_MT | | | H_MT | | |
| 2 | [100%] | | 55 | | | 109 | | |
| 3 | [100%] | | 55 | | | 109 | | |
| 4 | [100%] | | 55 | | | 109 | | |
| 5 | [100%] | | 55 | | | 109 | | |
| 6 | [100%] | | 55 | | | 109 | | |
| 7 | [100%] | | 55 | | | 109 | | |
| 11 | [100%] | | 48 | | | 96 | | |
| 12 | [100%] | | 49 | | | 98 | | |
| 13 | [100%] | | 50 | | | 100 | | |
| 14 | [100%] | | 54 | | | 107 | | |
| 17 | [100%] | | 54 | | | 108 | | |
| 18 | [50%] | | 21 | | | 58 | | |
| Hour | Part Load | | P_ICE | | | H_ICE | | |
| 1 | [50%] | | 76 | | | 174 | | |
| 8 | [100%] | | 157 | | | 258 | | |
| 9 | [100%] | | 172 | | | 282 | | |
| 10 | [100%] | | 172 | | | 282 | | |
| 11 | [100%] | | 172 | | | 282 | | |
| 12 | [100%] | | 172 | | | 282 | | |
| 13 | [100%] | | 172 | | | 282 | | |
| 14 | [100%] | | 172 | | | 282 | | |
| 15 | [100%], [50%] | | 151 [100%] (unit 1)<br>76 [50%] (unit 2) | | | 248 [100%] (unit 1)<br>174 [50%] (unit 2) | | |
| 16 | [100%], [50%] | | 151 [100%] (unit 1)<br>76 [50%] (unit 2) | | | 248 [100%] (unit 1)<br>174 [50%] (unit 2) | | |
| 17 | [100%] | | 172 | | | 282 | | |
| 18 | [100%] | | 168 | | | 276 | | |
| 19 | [75%] | | 124 | | | 237 | | |
| 20 | [50%] | | 93 | | | 212 | | |
| 21 | [50%] | | 83 | | | 189 | | |
| 22 | [50%] | | 77 | | | 176 | | |
| 23 | [50%] | | 79 | | | 180 | | |
| 24 | [50%] | | 76 | | | 174 | | |

### E.2.6 *Hourly LCA Optimization Model* for min $CO_2$ in a day in June

**Table 6-28: Supply from the energy systems in an average day in June (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 26 | 25 | 3 | 142 |
| 2 | 15 | 0 | 0 | 0 | 22 | 21 | 0 | 82 |
| 3 | 11 | 0 | 0 | 0 | 19 | 18 | 0 | 86 |
| 4 | 8 | 0 | 0 | 0 | 15 | 14 | 0 | 89 |
| 5 | 4 | 0 | 0 | 0 | 11 | 11 | 0 | 92 |
| 6 | 1 | 0 | 0 | 0 | 9 | 9 | 0 | 93 |
| 7 | 13 | 0 | 0 | 0 | 44 | 42 | 0 | 61 |
| 8 | 0 | 0 | 0 | 0 | 184 | 175 | 0 | 60 |
| 9 | 5 | 0 | 0 | 0 | 304 | 289 | 0 | 57 |
| 10 | 0 | 0 | 4 | 19 | 376 | 358 | 0 | 0 |
| 11 | 0 | 0 | 13 | 60 | 410 | 391 | 0 | 16 |
| 12 | 0 | 0 | 16 | 75 | 432 | 411 | 0 | 0 |
| 13 | 0 | 0 | 18 | 81 | 436 | 416 | 0 | 0 |
| 14 | 0 | 0 | 21 | 94 | 442 | 421 | 0 | 0 |
| 15 | 0 | 0 | 22 | 103 | 445 | 424 | 0 | 0 |
| 16 | 0 | 0 | 27 | 122 | 452 | 430 | 0 | 0 |
| 17 | 0 | 0 | 25 | 114 | 449 | 427 | 0 | 0 |
| 18 | 0 | 0 | 28 | 127 | 368 | 350 | 0 | 0 |
| 19 | 0 | 0 | 34 | 156 | 255 | 243 | 0 | 0 |
| 20 | 0 | 0 | 16 | 73 | 191 | 182 | 0 | 25 |
| 21 | 0 | 0 | 0 | 0 | 124 | 118 | 0 | 72 |
| 22 | 0 | 0 | 0 | 0 | 64 | 61 | 0 | 113 |
| 23 | 0 | 0 | 0 | 0 | 44 | 42 | 0 | 137 |
| 24 | 0 | 0 | 0 | 0 | 34 | 32 | 0 | 138 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [75%] | 34 | 79 |
| 10 | [100%] | 48 | 96 |
| 18 | [75%] | 35 | 81 |

**P_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 1 | [50%] | 76 | - |
| 8 | [100%] | 153 | 0 |
| 9 | [100%] | 172 | 0 |
| 10 | [100%] | 169 | 0 |

| Table 6-28 (continued) | | | |
|---|---|---|---|
| 11 | [100%] | 151 | 76 [50%] |
| 12 | [100%], [50%] | 155 | 76 [50%] |
| 13 | [100%], [50%] | 157 | 76 [50%] |
| 14 | [100%], [50%] | 160 | 76 [50%] |
| 15 | [100%], [50%] | 161 | 76 [50%] |
| 16 | [100%], [50%] | 167 | 76 [50%] |
| 17 | [100%], [50%] | 165 | 76 [50%] |
| 18 | [100%] | 172 | 0 |
| 19 | [100%] | 154 | 0 |
| 20 | [75%] | 113 | 0 |
| 21 | [50%] | 86 | - |
| 22 | [50%] | 79 | - |
| 23 | [50%] | 81 | - |
| 24 | [50%] | 77 | - |

**H_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 8 | [100%] | 251 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 278 | 0 |
| 11 | [100%], [50%] | 248 | 174 [50%] |
| 12 | [100%], [50%] | 255 | 174 [50%] |
| 13 | [100%], [50%] | 257 | 174 [50%] |
| 14 | [100%], [50%] | 262 | 174 [50%] |
| 15 | [100%], [50%] | 265 | 174 [50%] |
| 16 | [100%], [50%] | 274 | 174 [50%] |
| 17 | [100%], [50%] | 271 | 174 [50%] |
| 18 | [100%] | 282 | 0 |
| 19 | [100%] | 253 | 0 |
| 20 | [75%] | 215 | 0 |
| 21 | [50%] | 196 | 0 |
| 22 | [50%] | 180 | 0 |
| 23 | [50%] | 185 | 0 |
| 24 | [50%] | 176 | 0 |

## E.2.7 *Hourly LCA Optimization Model* for min $CO_2$ in a day in July

**Table 6-29: Supply from the energy systems in an average day in July (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 60 | 57 | 1 | 110 |
| 2 | 0 | 0 | 0 | 0 | 52 | 50 | 5 | 118 |
| 3 | 13 | 0 | 0 | 0 | 45 | 43 | 0 | 60 |
| 4 | 9 | 0 | 0 | 0 | 38 | 36 | 0 | 67 |
| 5 | 5 | 0 | 0 | 0 | 31 | 30 | 0 | 74 |
| 6 | 2 | 0 | 0 | 0 | 27 | 26 | 0 | 77 |
| 7 | 14 | 0 | 0 | 0 | 64 | 61 | 0 | 42 |
| 8 | 0 | 0 | 0 | 0 | 236 | 225 | 0 | 20 |
| 9 | 0 | 0 | 0 | 0 | 372 | 354 | 0 | 8 |
| 10 | 0 | 0 | 11 | 49 | 434 | 413 | 0 | 0 |
| 11 | 0 | 0 | 25 | 113 | 462 | 440 | 0 | 0 |
| 12 | 0 | 0 | 41 | 188 | 460 | 438 | 0 | 8 |
| 13 | 0 | 0 | 45 | 207 | 476 | 454 | 0 | 0 |
| 14 | 0 | 0 | 48 | 218 | 480 | 457 | 0 | 0 |
| 15 | 0 | 0 | 52 | 240 | 489 | 466 | 0 | 0 |
| 16 | 0 | 0 | 58 | 264 | 498 | 475 | 0 | 0 |
| 17 | 0 | 0 | 57 | 260 | 497 | 473 | 0 | 0 |
| 18 | 0 | 0 | 49 | 223 | 441 | 420 | 0 | 0 |
| 19 | 14 | 0 | 58 | 267 | 285 | 271 | 0 | 0 |
| 20 | 0 | 0 | 25 | 113 | 245 | 233 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 192 | 183 | 0 | 16 |
| 22 | 0 | 0 | 0 | 0 | 119 | 114 | 0 | 68 |
| 23 | 0 | 0 | 0 | 0 | 91 | 87 | 0 | 97 |
| 24 | 0 | 0 | 0 | 0 | 74 | 70 | 0 | 104 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |

**P_ICE**

| Hour | Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | - |
| 2 | [50%] | 76 | - |
| 8 | [100%] | 159 | 0 |
| 9 | [100%] | 172 | 0 |
| 10 | [100%], [50%] | 156 | 76 [50%] |

| Table 6-29 (continued) | | | |
|---|---|---|---|
| 11 | [100%], [50%] | 172 | 76 [50%] |
| 12 | [100%], [75%] | 151 | 113 [75%] |
| 13 | [100%], [75%] | 155 | 113 [75%] |
| 14 | [100%], [75%] | 158 | 113 [75%] |
| 15 | [100%], [75%] | 162 | 113 [75%] |
| 16 | [100%], [75%] | 169 | 113 [75%] |
| 17 | [100%], [75%] | 168 | 113 [75%] |
| 18 | [100%], [50%] | 159 | 76 [50%] |
| 19 | [100%] | 172 | 0 |
| 20 | [75%] | 127 | 0 |
| 21 | [50%] | 90 | 0 |
| 22 | [50%] | 82 | 0 |
| 23 | [50%] | 83 | 0 |
| 24 | [50%] | 79 | 0 |

**H_ICE**

| Hour | Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 8 | [100%] | 261 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%], [50%] | 256 | 174 [50%] |
| 11 | [100%], [50%] | 282 | 174 [50%] |
| 12 | [100%], [75%] | 248 | 215 [75%] |
| 13 | [100%], [75%] | 255 | 215 [75%] |
| 14 | [100%], [75%] | 259 | 215 [75%] |
| 15 | [100%], [75%] | 267 | 215 [75%] |
| 16 | [100%], [75%] | 277 | 215 [75%] |
| 17 | [100%], [75%] | 275 | 215 [75%] |
| 18 | [100%], [50%] | 260 | 174 [50%] |
| 19 | [100%] | 282 | 0 |
| 20 | [75%] | 241 | 0 |
| 21 | [50%] | 205 | 0 |
| 22 | [50%] | 187 | 0 |
| 23 | [50%] | 189 | 0 |
| 24 | [50%] | 180 | 0 |

### E.2.8 *Hourly LCA Optimization Model* for min $CO_2$ in a day in August

**Table 6-30: Supply from the energy systems in an average day in August (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 49 | 47 | 2 | 121 |
| 2 | 0 | 0 | 0 | 0 | 40 | 38 | 5 | 129 |
| 3 | 12 | 0 | 0 | 0 | 34 | 32 | 0 | 71 |
| 4 | 9 | 0 | 0 | 0 | 29 | 27 | 0 | 76 |
| 5 | 5 | 0 | 0 | 0 | 25 | 23 | 0 | 80 |
| 6 | 2 | 0 | 0 | 0 | 22 | 21 | 0 | 83 |
| 7 | 13 | 0 | 0 | 0 | 33 | 32 | 0 | 72 |
| 8 | 0 | 0 | 0 | 0 | 189 | 180 | 0 | 62 |
| 9 | 0 | 0 | 0 | 0 | 343 | 326 | 0 | 36 |
| 10 | 0 | 0 | 7 | 31 | 429 | 408 | 0 | 0 |
| 11 | 0 | 0 | 23 | 108 | 459 | 437 | 0 | 0 |
| 12 | 0 | 0 | 40 | 183 | 443 | 422 | 0 | 24 |
| 13 | 0 | 0 | 40 | 183 | 468 | 446 | 0 | 1 |
| 14 | 0 | 0 | 44 | 200 | 474 | 451 | 0 | 0 |
| 15 | 0 | 0 | 48 | 220 | 483 | 460 | 0 | 0 |
| 16 | 0 | 0 | 52 | 239 | 489 | 466 | 0 | 0 |
| 17 | 0 | 0 | 49 | 224 | 483 | 460 | 0 | 0 |
| 18 | 0 | 0 | 42 | 192 | 396 | 377 | 0 | 30 |
| 19 | 0 | 0 | 40 | 182 | 271 | 258 | 0 | 0 |
| 20 | 0 | 0 | 16 | 73 | 181 | 172 | 0 | 35 |
| 21 | 0 | 0 | 0 | 0 | 132 | 126 | 0 | 67 |
| 22 | 0 | 0 | 0 | 0 | 84 | 80 | 0 | 97 |
| 23 | 0 | 0 | 0 | 0 | 65 | 62 | 0 | 119 |
| 24 | 0 | 0 | 0 | 0 | 55 | 53 | 0 | 120 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 9 | [100%] | 48 | 96 |

**P_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 8 | [100%] | 158 | 0 |

| Table 6-30 (continued) | | | |
|---|---|---|---|
| 9 | [100%] | 172 | 0 |
| 10 | [100%], [50%] | 153 | 76 [50%] |
| 11 | [100%], [50%] | 170 | 76 [50%] |
| 12 | [100%], [75%] | 151 | 113 [75%] |
| 13 | [100%], [75%] | 151 | 113 [75%] |
| 14 | [100%], [75%] | 154 | 113 [75%] |
| 15 | [100%], [75%] | 159 | 113 [75%] |
| 16 | [100%], [75%] | 163 | 113 [75%] |
| 17 | [100%], [75%] | 160 | 113 [75%] |
| 18 | [100%], [50%] | 151 | 76 [50%] |
| 19 | [100%] | 164 | 0 |
| 20 | [75%] | 113 | 0 |
| 21 | [50%] | 87 | 0 |
| 22 | [50%] | 80 | 0 |
| 23 | [50%] | 82 | 0 |
| 24 | [50%] | 78 | 0 |

**H_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 8 | [100%] | 259 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%], [50%] | 251 | 174 [50%] |
| 11 | [100%], [50%] | 280 | 174 [50%] |
| 12 | [100%], [75%] | 248 | 215 [75%] |
| 13 | [100%], [75%] | 248 | 215 [75%] |
| 14 | [100%], [75%] | 252 | 215 [75%] |
| 15 | [100%], [75%] | 261 | 215 [75%] |
| 16 | [100%], [75%] | 268 | 215 [75%] |
| 17 | [100%], [75%] | 263 | 215 [75%] |
| 18 | [100%] | 248 | 174 [50%] |
| 19 | [100%] | 269 | 0 |
| 20 | [75%] | 215 | 0 |
| 21 | [50%] | 199 | 0 |
| 22 | [50%] | 183 | 0 |
| 23 | [50%] | 187 | 0 |
| 24 | [50%] | 178 | 0 |

### E.2.9 *Hourly LCA Optimization Model* for min $CO_2$ in a day in September

**Table 6-31: Supply from the energy systems in an average day in September (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 16 | 15 | 3 | 152 |
| 2 | 14 | 0 | 0 | 0 | 12 | 12 | 0 | 92 |
| 3 | 11 | 0 | 0 | 0 | 10 | 9 | 0 | 93 |
| 4 | 8 | 0 | 0 | 0 | 7 | 7 | 0 | 93 |
| 5 | 4 | 0 | 0 | 0 | 6 | 5 | 0 | 92 |
| 6 | 1 | 0 | 0 | 0 | 4 | 4 | 0 | 90 |
| 7 | 11 | 0 | 0 | 0 | 8 | 7 | 0 | 84 |
| 8 | 0 | 0 | 0 | 0 | 79 | 75 | 0 | 155 |
| 9 | 38 | 0 | 0 | 0 | 173 | 165 | 0 | 103 |
| 10 | 42 | 0 | 1 | 3 | 281 | 267 | 0 | 0 |
| 11 | 2 | 0 | 0 | 1 | 378 | 360 | 0 | 0 |
| 12 | 0 | 0 | 9 | 42 | 388 | 369 | 0 | 0 |
| 13 | 0 | 0 | 11 | 50 | 417 | 398 | 0 | 9 |
| 14 | 0 | 0 | 14 | 62 | 431 | 411 | 0 | 0 |
| 15 | 0 | 0 | 18 | 84 | 439 | 418 | 0 | 0 |
| 16 | 0 | 0 | 22 | 99 | 443 | 422 | 0 | 0 |
| 17 | 0 | 0 | 16 | 71 | 433 | 412 | 0 | 0 |
| 18 | 0 | 0 | 11 | 51 | 338 | 322 | 0 | 0 |
| 19 | 0 | 0 | 6 | 28 | 229 | 218 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 122 | 116 | 0 | 81 |
| 21 | 0 | 0 | 0 | 0 | 65 | 62 | 0 | 122 |
| 22 | 0 | 0 | 0 | 0 | 36 | 34 | 0 | 136 |
| 23 | 0 | 0 | 0 | 0 | 25 | 24 | 0 | 153 |
| 24 | 0 | 0 | 0 | 0 | 20 | 19 | 0 | 148 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 2 | [100%] | 55 | 109 |
| 3 | [100%] | 55 | 109 |
| 4 | [100%] | 55 | 109 |
| 5 | [100%] | 55 | 109 |
| 6 | [100%] | 55 | 109 |
| 7 | [100%] | 55 | 109 |
| 11 | [75%] | 40 | 93 |
| 12 | [100%] | 52 | 104 |
| 18 | [50%] | 21 | 58 |

**P_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 8 | [100%] | 152 | 0 |

| Table 6-31 (continued) | | | |
|---|---|---|---|
| 9 | [100%] | 172 | 0 |
| 10 | [100%] | 172 | 0 |
| 11 | [100%] | 172 | 0 |
| 12 | [100%] | 172 | 0 |
| 13 | [100%], [50%] | 151 | 76 [50%] |
| 14 | [100%], [50%] | 154 | 76 [50%] |
| 15 | [100%], [50%] | 158 | 76 [50%] |
| 16 | [100%], [50%] | 162 | 76 [50%] |
| 17 | [100%], [50%] | 156 | 76 [50%] |
| 18 | [100%] | 169 | 0 |
| 19 | [75%] | 120 | 0 |
| 20 | [50%] | 90 | 0 |
| 21 | [50%] | 83 | 0 |
| 22 | [50%] | 77 | 0 |
| 23 | [50%] | 80 | 0 |
| 24 | [50%] | 76 | 0 |

**H_ICE**

| Hour | Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 8 | [100%] | 250 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 282 | 0 |
| 11 | [100%] | 282 | 0 |
| 12 | [100%] | 282 | 0 |
| 13 | [100%], [50%] | 248 | 174 [50%] |
| 14 | [100%], [50%] | 252 | 174 [50%] |
| 15 | [100%], [50%] | 260 | 174 [50%] |
| 16 | [100%], [50%] | 265 | 174 [50%] |
| 17 | [100%], [50%] | 255 | 174 [50%] |
| 18 | [100%] | 277 | 0 |
| 19 | [75%] | 228 | 0 |
| 20 | [50%] | 205 | 0 |
| 21 | [50%] | 189 | 0 |
| 22 | [50%] | 176 | 0 |
| 23 | [50%] | 183 | 0 |
| 24 | [50%] | 174 | 0 |

### E.2.10 *Hourly LCA Optimization Model* for min $CO_2$ in a day in October

**Table 6-32: Supply from the energy systems in an average day in October (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 118 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 105 |
| 3 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 26 |
| 4 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 13 |
| 5 | 8 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 5 | 14 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 49 |
| 8 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 143 |
| 9 | 43 | 0 | 0 | 0 | 24 | 23 | 0 | 230 |
| 10 | 44 | 0 | 0 | 0 | 107 | 102 | 0 | 165 |
| 11 | 45 | 0 | 0 | 0 | 208 | 198 | 0 | 68 |
| 12 | 47 | 0 | 0 | 1 | 279 | 265 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 321 | 306 | 0 | 55 |
| 14 | 0 | 0 | 0 | 0 | 351 | 335 | 0 | 27 |
| 15 | 0 | 0 | 0 | 0 | 376 | 358 | 0 | 6 |
| 16 | 0 | 0 | 0 | 0 | 372 | 355 | 0 | 6 |
| 17 | 0 | 0 | 0 | 0 | 324 | 308 | 0 | 51 |
| 18 | 9 | 0 | 0 | 0 | 224 | 214 | 0 | 55 |
| 19 | 0 | 0 | 0 | 0 | 70 | 67 | 6 | 137 |
| 20 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 171 |
| 21 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 172 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 158 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 151 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 132 |
| | | | | **P_MT** | | | | |
| Hour | Part Load | Unit 1 | | | Unit 2 | | | |
| 3 | [100%] | 55 | | | 109 | | | |
| 4 | [100%] | 55 | | | 109 | | | |
| 5 | [100%] | 55 | | | 109 | | | |
| 6 | [100%] | 55 | | | 109 | | | |
| 13 | [100%] | 48 | | | 96 | | | |
| 14 | [100%] | 48 | | | 96 | | | |
| 15 | [100%] | 49 | | | 98 | | | |
| 16 | [100%] | 48 | | | 96 | | | |
| 17 | [100%] | 48 | | | 96 | | | |
| **Hour** | **Part Load** | **P_ICE** | | | **H_ICE** | | | |
| 1 | [50%] | 76 | | | 174 | | | |
| 2 | [50%] | 76 | | | 174 | | | |
| 7 | [50%] | 76 | | | 174 | | | |

| Table 6-32 (continued) | | | |
|---|---|---|---|
| 8 | [100%] | 156 | 256 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 171 | 281 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 171 | 281 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 85 | 194 |
| 21 | [50%] | 80 | 183 |
| 22 | [50%] | 76 | 174 |
| 23 | [50%] | 79 | 180 |
| 24 | [50%] | 77 | 176 |

### E.2.11 *Hourly LCA Optimization Model* for min $CO_2$ in a day in November

**Table 6-33: Supply from the energy systems in an average day in November (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 46 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 61 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 75 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 83 | 0 | 0 | 0 | 0 | 3 | 0 |
| 5 | 0 | 90 | 0 | 0 | 0 | 0 | 6 | 0 |
| 6 | 0 | 97 | 0 | 0 | 0 | 0 | 9 | 0 |
| 7 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 26 |
| 9 | 32 | 0 | 0 | 0 | 12 | 11 | 0 | 161 |
| 10 | 31 | 0 | 0 | 0 | 40 | 38 | 0 | 189 |
| 11 | 31 | 0 | 0 | 0 | 67 | 63 | 0 | 185 |
| 12 | 32 | 0 | 0 | 0 | 106 | 101 | 0 | 152 |
| 13 | 32 | 0 | 0 | 0 | 137 | 131 | 0 | 124 |
| 14 | 33 | 0 | 0 | 0 | 157 | 149 | 0 | 108 |
| 15 | 33 | 0 | 0 | 0 | 168 | 160 | 0 | 88 |
| 16 | 32 | 0 | 0 | 0 | 141 | 134 | 0 | 102 |
| 17 | 31 | 0 | 0 | 0 | 76 | 73 | 0 | 146 |
| 18 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 178 |
| 19 | 0 | 0 | 0 | 0 | 2 | 2 | 13 | 131 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 77 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35 |

| Table 6-33 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 22 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 76 | 174 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |
| 8 | [100%] | 151 | 248 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 168 | 276 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 86 | 196 |
| 21 | [50%] | 85 | 194 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 88 | 201 |
| 24 | [50%] | 85 | 194 |

### E.2.12 *Hourly LCA Optimization Model* for min $CO_2$ in a day in December

**Table 6-34: Supply from the energy systems in an average day in December (Hourly model: min $CO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 178 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 194 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 210 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 223 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 235 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 244 | 0 | 0 | 0 | 0 | 2 | 0 |
| 7 | 0 | 217 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 41 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |

| Table 6-34 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | 40 | 0 | 0 | 0 | 5 | 4 | 0 | 92 |
| 11 | 39 | 0 | 0 | 0 | 15 | 15 | 0 | 140 |
| 12 | 39 | 0 | 0 | 0 | 29 | 28 | 0 | 156 |
| 13 | 39 | 0 | 0 | 0 | 57 | 55 | 0 | 139 |
| 14 | 40 | 0 | 0 | 0 | 78 | 75 | 0 | 127 |
| 15 | 41 | 0 | 0 | 0 | 81 | 77 | 0 | 126 |
| 16 | 40 | 0 | 0 | 0 | 52 | 49 | 0 | 140 |
| 17 | 39 | 0 | 0 | 0 | 16 | 15 | 0 | 127 |
| 18 | 3 | 0 | 0 | 0 | 6 | 6 | 0 | 77 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 17 |
| 20 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 133 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 139 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 77 | 176 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 79 (unit 1)<br>79 (unit 2) | 180 (unit 1)<br>180 (unit 2) |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 172 | 282 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 94 | 215 |
| 21 | [50%] | 92 | 210 |
| 22 | [50%] | 90 | 205 |
| 23 | [50%] | 94 | 215 |
| 24 | [50%] | 91 | 208 |

## E.3 AVERAGE ELECTRIC OPTION: MIN AP

### E.3.1 *Hourly LCA Optimization Model* for min AP in a day in January

**Table 6-35: Supply from the energy systems in an average day in January (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_E | C_E | C_A | H_A | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 102 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 109 | 0 |
| 3 | 0 | 7 | 0 | 0 | 0.00 | 0.00 | 113 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 122 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 130 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 136 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 121 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 59 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 | 91 |
| 10 | 0 | 0 | 0 | 0 | 0.72 | 0.69 | 0 | 204 |
| 11 | 0 | 0 | 0 | 0 | 8.72 | 8.30 | 0 | 269 |
| 12 | 0 | 0 | 0 | 0 | 22.20 | 21.14 | 0 | 286 |
| 13 | 0 | 0 | 0 | 0 | 35.30 | 33.62 | 0 | 292 |
| 14 | 0 | 0 | 0 | 0 | 53.80 | 51.24 | 0 | 287 |
| 15 | 0 | 0 | 0 | 0 | 70.20 | 66.86 | 0 | 264 |
| 16 | 0 | 0 | 0 | 0 | 63.30 | 60.29 | 0 | 246 |
| 17 | 0 | 0 | 0 | 0 | 28.10 | 26.76 | 0 | 230 |
| 18 | 0 | 0 | 0 | 0 | 1.57 | 1.50 | 1 | 105 |
| 19 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 5 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 45 | 0 |
| 21 | 0 | 1 | 0 | 0 | 0.00 | 0.00 | 65 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 82 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 86 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 97 | 0 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 1 | [75%] | 40 | 39 | 39 | 39 | 39 | 0 |
| 2 | [75%] | 40 | 40 | 40 | 40 | 40 | 0 |
| 3 | [75%] | 40 | 40 | 40 | 40 | 40 | 0 |
| 4 | [75%] | 35 | 35 | 34 | 34 | 34 | 34 |
| 5 | [75%] | 40 | 34 | 34 | 34 | 34 | 34 |
| 6 | [75%] | 40 | 38 | 34 | 34 | 34 | 34 |
| 7 | [75%] | 39 | 34 | 34 | 34 | 34 | 34 |
| 8 | [75%] | 40 | 36 | 36 | 36 | 36 | 36 |
| 9 | [100 %] | 55 | 53 | 53 | 53 | 0 | 0 |
| 10 | [100 %] | 55 | 55 | 51 | 51 | 0 | 0 |
| 11 | [100 %] | 55 | 54 | 54 | 48 | 0 | 0 |

| Table 6-35 (continued) | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | [100 %] | 55 | 55 | 51 | 51 | 0 | 0 |
| 13 | [100 %] | 55 | 52 | 52 | 52 | 0 | 0 |
| 14 | [100 %] | 55 | 52 | 52 | 52 | 0 | 0 |
| 15 | [100 %] | 54 | 54 | 54 | 48 | 0 | 0 |
| 16 | [100 %] | 55 | 55 | 51 | 51 | 0 | 0 |
| 17 | [100 %] | 55 | 52 | 52 | 52 | 0 | 0 |
| 18 | [100 %] | 48 | 48 | 48 | 0 | 0 | 0 |
| 19 | [75%] | 0 | 0 | 0 | 34 | 0 | 0 |
| 20 | [75%] | 40 | 37 | 37 | 0 | 0 | 0 |
| 21 | [75%] | 40 | 34 | 34 | 34 | 0 | 0 |
| 22 | [75%] | 40 | 40 | 40 | 40 | 0 | 0 |
| 23 | [75%] | 35 | 35 | 35 | 35 | 35 | 0 |
| 24 | [75%] | 40 | 37 | 37 | 37 | 34 | 0 |

**H_MT**

| Hour | MT No. Part Load | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 1 | [75%] | 93 | 90 | 90 | 90 | 90 | 0 |
| 2 | [75%] | 93 | 92 | 92 | 92 | 92 | 0 |
| 3 | [75%] | 93 | 93 | 93 | 93 | 93 | 0 |
| 4 | [75%] | 82 | 82 | 79 | 79 | 79 | 79 |
| 5 | [75%] | 93 | 80 | 80 | 80 | 80 | 79 |
| 6 | [75%] | 93 | 89 | 79 | 79 | 79 | 79 |
| 7 | [75%] | 91 | 79 | 79 | 79 | 79 | 79 |
| 8 | [75%] | 93 | 83 | 83 | 83 | 83 | 83 |
| 9 | [100%] | 109 | 106 | 106 | 106 | 0 | 0 |
| 10 | [100%] | 109 | 109 | 102 | 102 | 0 | 0 |
| 11 | [100%] | 109 | 108 | 108 | 96 | 0 | 0 |
| 12 | [100%] | 109 | 109 | 101 | 101 | 0 | 0 |
| 13 | [100%] | 109 | 104 | 104 | 104 | 0 | 0 |
| 14 | [100%] | 109 | 104 | 104 | 104 | 0 | 0 |
| 15 | [100%] | 108 | 108 | 108 | 96 | 0 | 0 |
| 16 | [100%] | 109 | 109 | 102 | 102 | 0 | 0 |
| 17 | [100%] | 109 | 104 | 104 | 104 | 0 | 0 |
| 18 | [100%] | 96 | 96 | 96 | 0 | 0 | 0 |
| 19 | [75%] | 0 | 0 | 0 | 79 | 0 | 0 |
| 20 | [75%] | 93 | 87 | 87 | 0 | 0 | 0 |
| 21 | [75%] | 93 | 79 | 79 | 79 | 0 | 0 |
| 22 | [75%] | 93 | 93 | 93 | 93 | 0 | 0 |
| 23 | [75%] | 82 | 82 | 82 | 82 | 82 | 0 |
| 24 | [75%] | 93 | 86 | 86 | 86 | 79 | 0 |

## E.3.2 *Hourly LCA Optimization Model* for min AP in a day in February

**Table 6-36: Supply from the energy systems in an average day in February (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 135 | 0 |
| 2 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 144 | 0 |
| 3 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 151 | 0 |
| 4 | 0 | 12 | 0.0 | 0.0 | 0.0 | 0.0 | 154 | 0 |
| 5 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 167 | 1 |
| 6 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 174 | 0 |
| 7 | 0 | 18 | 0.0 | 0.0 | 0.0 | 0.0 | 150 | 0 |
| 8 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 70 | 0 |
| 9 | 0 | 0 | 0.0 | 0.0 | 0.3 | 0.3 | 0 | 36 |
| 10 | 0 | 0 | 0.0 | 0.0 | 21.2 | 20.2 | 0 | 113 |
| 11 | 0 | 0 | 0.0 | 0.0 | 41.1 | 39.1 | 0 | 135 |
| 12 | 0 | 0 | 0.0 | 0.0 | 64.5 | 61.4 | 0 | 139 |
| 13 | 0 | 0 | 0.0 | 0.0 | 85.7 | 81.6 | 0 | 138 |
| 14 | 0 | 0 | 0.0 | 0.0 | 96.9 | 92.3 | 0 | 129 |
| 15 | 0 | 0 | 0.0 | 0.0 | 121.3 | 115.6 | 0 | 101 |
| 16 | 0 | 0 | 0.0 | 0.0 | 120.0 | 114.3 | 0 | 87 |
| 17 | 0 | 0 | 0.0 | 0.0 | 96.5 | 91.9 | 0 | 95 |
| 18 | 0 | 0 | 0.0 | 0.0 | 26.8 | 25.6 | 0 | 43 |
| 19 | 0 | 19 | 0.2 | 0.8 | 0.0 | 0.0 | 9 | 0 |
| 20 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 52 | 0 |
| 21 | 0 | 25 | 0.0 | 0.0 | 0.0 | 0.0 | 65 | 0 |
| 22 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 100 | 0 |
| 23 | 0 | 20 | 0.0 | 0.0 | 0.0 | 0.0 | 101 | 0 |
| 24 | 0 | 25 | 0.0 | 0.0 | 0.0 | 0.0 | 103 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [62%] | 75 | 31 |
| 9 | [93%] | 116 | 77 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 116 | 77 |
| 12 | [93%] | 116 | 77 |
| 13 | [93%] | 116 | 77 |
| 14 | [93%] | 116 | 77 |

Table 6-36 (continued)

| | | | |
|---|---|---|---|
| 15 | [93%] | 116 | 77 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 116 | 77 |
| 18 | [100%] | 127 | 99 |
| 19 | [62%] | 75 | 31 |
| 20 | [62%] | 75 | 31 |
| 21 | [62%] | 75 | 31 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 37 | 37 | 37 | 37 | 0 |
| 2 | [75%] | 40 | 40 | 40 | 35 | 0 |
| 3 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 4 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 5 | [75%] | 34 | 34 | 34 | 34 | 34 |
| 6 | [75%] | 35 | 35 | 35 | 35 | 35 |
| 7 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 8 | [75%] | 40 | 38 | 38 | 38 | 0 |
| 9 | [100] | 48 | 48 | 0 | 0 | 0 |
| 10 | [100] | 48 | 48 | 0 | 0 | 0 |
| 11 | [100] | 48 | 48 | 0 | 0 | 0 |
| 12 | [100] | 48 | 48 | 0 | 0 | 0 |
| 13 | [100] | 48 | 48 | 0 | 0 | 0 |
| 14 | [100] | 48 | 48 | 0 | 0 | 0 |
| 15 | [100] | 48 | 48 | 0 | 0 | 0 |
| 16 | [100] | 48 | 48 | 0 | 0 | 0 |
| 17 | [100] | 48 | 48 | 0 | 0 | 0 |
| 18 | [100] | 49 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 40 | 0 | 0 | 0 | 0 |
| 20 | [75%] | 34 | 34 | 0 | 0 | 0 |
| 21 | [75%] | 40 | 40 | 0 | 0 | 0 |
| 22 | [75%] | 38 | 38 | 38 | 0 | 0 |
| 23 | [75%] | 40 | 40 | 40 | 0 | 0 |
| 24 | [75%] | 40 | 40 | 40 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 87 | 87 | 87 | 87 | 0 |
| 2 | [75%] | 93 | 93 | 93 | 82 | 0 |
| 3 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 4 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 5 | [75%] | 79 | 79 | 79 | 79 | 79 |
| 6 | [75%] | 81 | 81 | 81 | 81 | 81 |
| 7 | [75%] | 93 | 93 | 93 | 93 | 0 |

| Table 6-36 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 8 | [75%] | 93 | 88 | 88 | 88 | 0 |
| 9 | [100] | 96 | 96 | 0 | 0 | 0 |
| 10 | [100] | 96 | 96 | 0 | 0 | 0 |
| 11 | [100] | 96 | 96 | 0 | 0 | 0 |
| 12 | [100] | 96 | 96 | 0 | 0 | 0 |
| 13 | [100] | 96 | 96 | 0 | 0 | 0 |
| 14 | [100] | 96 | 96 | 0 | 0 | 0 |
| 15 | [100] | 96 | 96 | 0 | 0 | 0 |
| 16 | [100] | 96 | 96 | 0 | 0 | 0 |
| 17 | [100] | 96 | 96 | 0 | 0 | 0 |
| 18 | [100] | 97 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 93 | 0 | 0 | 0 | 0 |
| 20 | [75%] | 80 | 80 | 0 | 0 | 0 |
| 21 | [75%] | 93 | 93 | 0 | 0 | 0 |
| 22 | [75%] | 88 | 88 | 88 | 0 | 0 |
| 23 | [75%] | 93 | 93 | 93 | 0 | 0 |
| 24 | [75%] | 93 | 93 | 93 | 0 | 0 |

### E.3.3 *Hourly LCA Optimization Model* for min AP in a day in March

**Table 6-37: Supply from the energy systems in an average day in March (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 24 | 0 | 0 | 0 | 0 | 72 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 87 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 109 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 116 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 122 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 102 | 0 |
| 8 | 0 | 22 | 0 | 1 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 35 | 33 | 0 | 108 |
| 10 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 105 |
| 11 | 0 | 0 | 0 | 0 | 131 | 124 | 0 | 87 |
| 12 | 0 | 0 | 0 | 0 | 156 | 149 | 0 | 72 |
| 13 | 0 | 0 | 0 | 0 | 178 | 170 | 0 | 61 |
| 14 | 0 | 0 | 0 | 0 | 209 | 199 | 0 | 36 |
| 15 | 0 | 0 | 0 | 0 | 222 | 211 | 0 | 21 |
| 16 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 13 |
| 17 | 0 | 0 | 0 | 0 | 180 | 171 | 0 | 44 |
| 18 | 0 | 0 | 0 | 0 | 102 | 97 | 0 | 25 |
| 19 | 0 | 1 | 5 | 25 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 2 | 8 | 0 | 0 | 9 | 0 |

Table 6-37 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 21 | 0 | 11 | 1 | 3 | 0 | 0 | 29 | 0 |
| 22 | 0 | 0 | 0 | 1 | 0 | 0 | 50 | 0 |
| 23 | 0 | 0 | 0 | 1 | 0 | 0 | 63 | 0 |
| 24 | 0 | 6 | 0 | 0 | 0 | 0 | 69 | 0 |

| **Hour** | **Percent Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [62%] | 75 | 31 |
| 9 | [93%] | 115 | 77 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 117 | 78 |
| 12 | [93%] | 118 | 79 |
| 13 | [93%] | 118 | 79 |
| 14 | [93%] | 119 | 79 |
| 15 | [93%] | 119 | 79 |
| 16 | [93%] | 119 | 79 |
| 17 | [93%] | 118 | 79 |
| 18 | [100%] | 127 | 99 |
| 19 | [85%] | 109 | 67 |
| 20 | [62%] | 75 | 31 |
| 21 | [62%] | 75 | 31 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | [75%] | 40 | 40 | 0 |
| 2 | [75%], [50%] | 37 [75%] | 34 [75%] | 21 [50%] |
| 3 | [75%] | 34 | 34 | 34 |
| 4 | [75%] | 40 | 34 | 34 |
| 5 | [75%] | 40 | 38 | 34 |
| 6 | [75%] | 39 | 39 | 39 |
| 7 | [75%] | 37 | 34 | 34 |
| 8 | [75%] | 40 | 40 | 0 |
| 9 | [100%] | 48 | 48 | 0 |
| 10 | [100%] | 48 | 48 | 0 |
| 11 | [100%] | 48 | 48 | 0 |
| 12 | [100%] | 48 | 48 | 0 |

| Table 6-37 (continued) | | | | |
|---|---|---|---|---|
| 13 | [100%] | 48 | 48 | 0 |
| 14 | [100%] | 48 | 48 | 0 |
| 15 | [100%] | 48 | 48 | 0 |
| 16 | [100%] | 48 | 48 | 0 |
| 17 | [100%] | 48 | 48 | 0 |
| 18 | [100%] | 49 | 0 | 0 |
| 20 | [50%] | 23 | 0 | 0 |
| 21 | [75%] | 40 | 0 | 0 |
| 22 | [75%], [50%] | 39 [75%] | 21 [50%] | 0 |
| 23 | [75%] | 38 | 38 | 0 |
| 24 | [75%] | 40 | 40 | 0 |
| | | **H_MT** | | |
| Hour | MT No. / Part Load | 1 | 2 | 3 |
| 1 | [75%] | 93 | 93 | 0 |
| 2 | [75%], [50%] | 86 [75%] | 79 [75%] | 58 [50%] |
| 3 | [75%] | 79 | 79 | 79 |
| 4 | [75%] | 93 | 80 | 80 |
| 5 | [75%] | 93 | 89 | 79 |
| 6 | [75%] | 90 | 90 | 90 |
| 7 | [75%] | 86 | 79 | 79 |
| 8 | [75%] | 93 | 93 | 0 |
| 9 | [100%] | 96 | 96 | 0 |
| 10 | [100%] | 96 | 96 | 0 |
| 11 | [100%] | 96 | 96 | 0 |
| 12 | [100%] | 96 | 96 | 0 |
| 13 | [100%] | 96 | 96 | 0 |
| 14 | [100%] | 96 | 96 | 0 |
| 15 | [100%] | 96 | 96 | 0 |
| 16 | [100%] | 96 | 96 | 0 |
| 17 | [100%] | 96 | 96 | 0 |
| 18 | [100%] | 97 | 0 | 0 |
| 20 | [50%] | 66 | 0 | 0 |
| 21 | [75%] | 93 | 0 | 0 |
| 22 | [75%], [50%] | 90 [75%] | 58 [50%] | 0 |
| 23 | [75%] | 88 | 88 | 0 |
| 24 | [75%] | 93 | 93 | 0 |

### E.3.4 *Hourly LCA Optimization Model* for min AP in a day in April

**Table 6-38: Supply from the energy systems in an average day in April (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 0 | 0 | 0 | 0 | 17 | 0 |
| 2 | 0 | 33 | 0 | 0 | 0 | 0 | 4 | 0 |
| 3 | 0 | 50 | 0 | 0 | 0 | 0 | 7 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 46 | 0 |
| 6 | 0 | 5 | 0 | 0 | 0 | 0 | 54 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 1 |
| 8 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 83 |
| 9 | 0 | 0 | 0 | 0 | 45 | 43 | 0 | 205 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 0 | 143 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 0 | 83 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 0 | 34 |
| 13 | 0 | 0 | 0 | 0 | 274 | 261 | 0 | 10 |
| 14 | 0 | 0 | 4 | 21 | 294 | 280 | 0 | 0 |
| 15 | 0 | 0 | 7 | 30 | 310 | 296 | 0 | 0 |
| 16 | 0 | 0 | 8 | 39 | 313 | 298 | 0 | 0 |
| 17 | 0 | 0 | 6 | 28 | 306 | 292 | 0 | 0 |
| 18 | 0 | 0 | 7 | 34 | 237 | 226 | 0 | 0 |
| 19 | 0 | 0 | 14 | 66 | 88 | 84 | 0 | 0 |
| 20 | 0 | 0 | 5 | 21 | 41 | 39 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 8 |
| 22 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 7 |
| 23 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 7 |
| 24 | 0 | 2 | 0 | 0 | 0 | 0 | 14 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |

| Table 6-38 (continued) | | | |
|---|---|---|---|
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |
| 17 | [104%] | 130 | 109 |
| 18 | [85%] | 110 | 68 |
| 19 | [100%] | 127 | 99 |
| 20 | [78%] | 95 | 53 |
| 21 | [68%] | 82 | 39 |
| 22 | [62%] | 76 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No.<br>Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 4 | [50%] | 23 | 0 |
| 5 | [75%] | 35 | 0 |
| 6 | [75%] | 40 | 0 |
| 7 | [75%] | 34 | 0 |
| 8 | [100%] | 49 | 0 |
| 9 | [100%] | 52 | 48 |
| 10 | [100%] | 53 | 48 |
| 11 | [100%] | 51 | 51 |
| 12 | [100%] | 55 | 48 |
| 13 | [100%] | 55 | 49 |
| 14 | [100%] | 55 | 53 |
| 15 | [100%] | 51 | 51 |
| 16 | [100%] | 52 | 52 |
| 17 | [100%] | 50 | 50 |
| 18 | [100%], [75%] | 48 [100%] | 34 [75%] |

**H_MT**

| Hour | MT No.<br>Part Load | Unit 1 | Unit 2 |
|---|---|---|---|
| 4 | [50%] | 65 | 0 |
| 5 | [75%] | 81 | 0 |
| 6 | [75%] | 93 | 0 |
| 7 | [75%] | 79 | 0 |
| 8 | [100%] | 98 | 0 |
| 9 | [100%] | 103 | 96 |
| 10 | [100%] | 105 | 96 |
| 11 | [100%] | 101 | 101 |
| 12 | [100%] | 109 | 96 |
| 13 | [100%] | 109 | 97 |
| 14 | [100%] | 109 | 106 |
| 15 | [100%] | 101 | 101 |
| 16 | [100%] | 103 | 103 |
| 17 | [100%] | 100 | 100 |
| 18 | [100%], [75%] | 96 [100%] | 79 [75%] |

### E.3.5 *Hourly LCA Optimization Model* for min AP in a day in May

**Table 6-39: Supply from the energy systems in an average day in May (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 2 | 7 | 0 | 0 | 1 | 22 |
| 2 | 0 | 0 | 0 | 0 | 5 | 5 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 3 | 3 | 9 | 11 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 12 | 8 |
| 5 | 0 | 0 | 0 | 1 | 0 | 0 | 15 | 6 |
| 6 | 0 | 0 | 0 | 1 | 0 | 0 | 18 | 0 |
| 7 | 0 | 0 | 0 | 0 | 7 | 7 | 8 | 3 |
| 8 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 82 |
| 9 | 0 | 0 | 0 | 0 | 163 | 155 | 0 | 104 |
| 10 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 18 |
| 11 | 0 | 0 | 8 | 37 | 293 | 279 | 0 | 0 |
| 12 | 0 | 0 | 12 | 56 | 313 | 298 | 0 | 0 |
| 13 | 0 | 0 | 15 | 69 | 320 | 305 | 0 | 0 |
| 14 | 0 | 0 | 18 | 82 | 328 | 312 | 0 | 0 |
| 15 | 0 | 0 | 20 | 89 | 340 | 324 | 0 | 0 |
| 16 | 0 | 0 | 22 | 99 | 343 | 327 | 0 | 0 |
| 17 | 0 | 3 | 19 | 86 | 329 | 314 | 0 | 0 |
| 18 | 0 | 0 | 22 | 102 | 259 | 247 | 0 | 0 |
| 19 | 0 | 0 | 27 | 123 | 143 | 136 | 0 | 0 |
| 20 | 0 | 0 | 18 | 82 | 65 | 62 | 0 | 4 |
| 21 | 0 | 0 | 4 | 17 | 37 | 36 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 23 | 22 | 0 | 4 |
| 23 | 0 | 0 | 0 | 0 | 15 | 14 | 0 | 12 |
| 24 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 16 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 109 | 67 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [104%] | 130 | 109 |
| 13 | [104%] | 130 | 109 |

Table 6-39 (continued)

| | | | |
|---|---|---|---|
| 14 | [104%] | 130 | 109 |
| 15 | [85%] | 111 | 68 |
| 16 | [85%] | 111 | 68 |
| 17 | [104%] | 130 | 109 |
| 18 | [93%] | 120 | 80 |
| 19 | [85%] | 111 | 68 |
| 20 | [93%] | 111 | 74 |
| 21 | [68%] | 87 | 42 |
| 22 | [62%] | 77 | 32 |
| 23 | [62%] | 79 | 33 |
| 24 | [62%] | 76 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 50 | 48 | 0 |
| 10 | [100%] | 51 | 48 | 0 |
| 11 | [100%] | 55 | 53 | 0 |
| 12 | [100%] | 55 | 48 | 0 |
| 13 | [100%] | 53 | 53 | 0 |
| 14 | [100%] | 55 | 55 | 0 |
| 15 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 16 | [100%], [75%] | 49 [100%] | 49 [100%] | 34 [75%] |
| 17 | [100%] | 55 | 55 | 0 |
| 18 | [100%], [75%] | 51 [100%] | 34 [75%] | 0 |
| 19 | [75%] | 34 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 99 | 96 | 0 |
| 10 | [100%] | 101 | 96 | 0 |
| 11 | [100%] | 109 | 105 | 0 |
| 12 | [100%] | 109 | 96 | 0 |
| 13 | [100%] | 106 | 106 | 0 |
| 14 | [100%] | 109 | 109 | 0 |
| 15 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 16 | [100%], [75%] | 98 [100%] | 98 [100%] | 79 [75%] |
| 17 | [100%] | 109 | 109 | 0 |
| 18 | [100%], [75%] | 101 [100%] | 79 [75%] | 0 |
| 19 | [75%] | 79 [75%] | 0 | 0 |

### E.3.6 *Hourly LCA Optimization Model* for min AP in a day in June

**Table 6-40: Supply from the energy systems in an average day in June (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 2 | 7 | 19 | 19 | 0 | 6 |
| 2 | 0 | 0 | 0 | 0 | 22 | 21 | 5 | 4 |
| 3 | 0 | 0 | 0 | 0 | 19 | 18 | 9 | 7 |
| 4 | 0 | 0 | 0 | 0 | 15 | 14 | 12 | 11 |
| 5 | 0 | 0 | 0 | 0 | 11 | 11 | 16 | 13 |
| 6 | 0 | 0 | 0 | 0 | 9 | 9 | 19 | 14 |
| 7 | 0 | 0 | 7 | 30 | 14 | 14 | 0 | 11 |
| 8 | 0 | 0 | 6 | 28 | 156 | 148 | 0 | 0 |
| 9 | 0 | 0 | 7 | 31 | 272 | 259 | 0 | 0 |
| 10 | 0 | 0 | 18 | 84 | 311 | 296 | 0 | 0 |
| 11 | 0 | 0 | 28 | 128 | 342 | 326 | 0 | 0 |
| 12 | 0 | 0 | 34 | 157 | 350 | 333 | 0 | 0 |
| 13 | 0 | 0 | 36 | 164 | 353 | 337 | 0 | 0 |
| 14 | 0 | 0 | 39 | 180 | 356 | 339 | 0 | 0 |
| 15 | 0 | 0 | 41 | 188 | 359 | 342 | 0 | 0 |
| 16 | 0 | 0 | 45 | 208 | 366 | 348 | 0 | 0 |
| 17 | 0 | 0 | 43 | 199 | 364 | 347 | 0 | 0 |
| 18 | 0 | 0 | 45 | 207 | 288 | 274 | 0 | 0 |
| 19 | 0 | 0 | 51 | 232 | 179 | 170 | 0 | 0 |
| 20 | 0 | 7 | 33 | 151 | 113 | 108 | 0 | 0 |
| 21 | 0 | 0 | 15 | 71 | 53 | 51 | 0 | 0 |
| 22 | 0 | 0 | 6 | 27 | 37 | 35 | 0 | 0 |
| 23 | 0 | 0 | 2 | 9 | 36 | 34 | 0 | 0 |
| 24 | 0 | 0 | 1 | 6 | 28 | 26 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [104%] | 130 | 109 |
| 11 | [85%] | 111 | 68 |
| 12 | [93%] | 119 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [85%] | 110 | 68 |
| 15 | [85%] | 111 | 68 |
| 16 | [93%] | 117 | 78 |

Table 6-40 (continued)

| | | | |
|---|---|---|---|
| 17 | [93%] | 115 | 77 |
| 18 | [93%] | 120 | 80 |
| 19 | [93%] | 120 | 80 |
| 20 | [104%] | 130 | 109 |
| 21 | [78%] | 101 | 57 |
| 22 | [68%] | 85 | 41 |
| 23 | [68%] | 83 | 40 |
| 24 | [62%] | 78 | 32 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 49 | 49 | 0 |
| 10 | [100%] | 51 | 51 | 0 |
| 11 | [100%], [75%] | 49 [100%] | 49 [100%] | 34 [75%] |
| 12 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 13 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 14 | [100%] | 48 | 48 | 48 |
| 15 | [100%] | 48 | 48 | 48 |
| 16 | [100%] | 48 | 48 | 48 |
| 17 | [100%] | 48 | 48 | 48 |
| 18 | [100%] | 55 | 49 | 0 |
| 19 | [100%] | 50 | 0 | 0 |

**H_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 97 | 97 | 0 |
| 10 | [100%] | 101 | 101 | 0 |
| 11 | [100%], [75%] | 97 [100%] | 97 [100%] | 79 [75%] |
| 12 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 13 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 14 | [100%] | 96 | 96 | 96 |
| 15 | [100%] | 96 | 96 | 96 |
| 16 | [100%] | 96 | 96 | 96 |
| 17 | [100%] | 96 | 96 | 96 |
| 18 | [100%] | 109 | 98 | 0 |
| 19 | [100%] | 100 | 0 | 0 |

### E.3.7 *Hourly LCA Optimization Model* for min AP in a day in July

**Table 6-41: Supply from the energy systems in an average day in July (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 7 | 30 | 30 | 29 | 0 | 4 |
| 2 | 0 | 0 | 6 | 25 | 27 | 25 | 0 | 0 |
| 3 | 0 | 0 | 7 | 30 | 15 | 15 | 0 | 10 |
| 4 | 0 | 0 | 8 | 38 | 0 | 0 | 2 | 25 |
| 5 | 0 | 0 | 7 | 31 | 0 | 0 | 8 | 25 |
| 6 | 0 | 0 | 6 | 27 | 0 | 0 | 12 | 25 |
| 7 | 0 | 0 | 8 | 37 | 27 | 26 | 0 | 0 |
| 8 | 0 | 0 | 13 | 61 | 175 | 167 | 0 | 0 |
| 9 | 0 | 0 | 13 | 59 | 313 | 298 | 0 | 0 |
| 10 | 0 | 0 | 29 | 132 | 351 | 334 | 0 | 0 |
| 11 | 0 | 0 | 44 | 201 | 374 | 356 | 0 | 0 |
| 12 | 0 | 0 | 55 | 252 | 396 | 377 | 0 | 0 |
| 13 | 0 | 0 | 60 | 275 | 408 | 388 | 0 | 0 |
| 14 | 0 | 1 | 62 | 284 | 414 | 394 | 0 | 0 |
| 15 | 0 | 0 | 65 | 300 | 429 | 409 | 0 | 0 |
| 16 | 0 | 0 | 70 | 322 | 440 | 419 | 0 | 0 |
| 17 | 0 | 0 | 69 | 318 | 439 | 418 | 0 | 0 |
| 18 | 0 | 0 | 67 | 305 | 358 | 341 | 0 | 0 |
| 19 | 0 | 0 | 67 | 305 | 247 | 235 | 0 | 0 |
| 20 | 0 | 0 | 45 | 206 | 152 | 144 | 0 | 0 |
| 21 | 0 | 0 | 26 | 118 | 75 | 71 | 0 | 0 |
| 22 | 0 | 0 | 15 | 69 | 51 | 48 | 0 | 0 |
| 23 | 0 | 0 | 9 | 43 | 48 | 46 | 0 | 0 |
| 24 | 0 | 0 | 8 | 36 | 38 | 36 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [68%] | 82 | 39 |
| 2 | [62%] | 77 | 31 |
| 3 | [62%] | 77 | 31 |
| 4 | [62%] | 77 | 31 |
| 5 | [62%] | 77 | 31 |
| 6 | [62%] | 77 | 31 |
| 7 | [62%] | 77 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [104%] | 130 | 109 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |

Table 6-41 (continued)

| | | | |
|---|---|---|---|
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |
| 17 | [104%] | 130 | 109 |
| 18 | [93%] | 120 | 80 |
| 19 | [85%] | 111 | 68 |
| 20 | [85%] | 111 | 68 |
| 21 | [93%] | 116 | 77 |
| 22 | [78%] | 97 | 54 |
| 23 | [78%] | 92 | 52 |
| 24 | [68%] | 87 | 42 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 52 | 0 | 0 |
| 9 | [100%] | 51 | 51 | 0 |
| 10 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 11 | [100%] | 49 | 49 | 48 |
| 12 | [100%] | 55 | 51 | 51 |
| 13 | [100%] | 54 | 54 | 54 |
| 14 | [100%] | 55 | 55 | 55 |
| 15 | [100%] | 55 | 55 | 49 |
| 16 | [100%] | 55 | 55 | 55 |
| 17 | [100%] | 54 | 54 | 54 |
| 18 | [100%], [75%] | 50 [100%] | 48 [100%] | 34 [75%] |
| 19 | [100%], [75%] | 50 [100%] | 34 [75%] | 0 |
| 20 | [75%] | 36 [75%] | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 103 | 0 | 0 |
| 9 | [100%] | 102 | 102 | 0 |
| 10 | [100%] , [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 11 | [100%] | 98 | 98 | 96 |
| 12 | [100%] | 109 | 102 | 102 |
| 13 | [100%] | 108 | 108 | 108 |
| 14 | [100%] | 109 | 109 | 109 |
| 15 | [100%] | 109 | 109 | 97 |
| 16 | [100%] | 109 | 109 | 109 |
| 17 | [100%] | 108 | 108 | 108 |
| 18 | [100%], [75%] | 100 [100%] | 96 [100%] | 79 [75%] |
| 19 | [100%], [75%] | [100%] 99 | 79 [75%] | 0 |
| 20 | [75%] | 84 [75%] | 0 | 0 |

### E.3.8 *Hourly LCA Optimization Model* for min AP in a day in August

**Table 6-42: Supply from the energy systems in an average day in August (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 5 | 21 | 28 | 26 | 0 | 0 |
| 2 | 0 | 0 | 4 | 16 | 24 | 23 | 0 | 2 |
| 3 | 0 | 0 | 2 | 8 | 26 | 25 | 6 | 0 |
| 4 | 0 | 0 | 6 | 29 | 0 | 0 | 4 | 25 |
| 5 | 0 | 0 | 5 | 25 | 0 | 0 | 9 | 25 |
| 6 | 0 | 0 | 5 | 22 | 0 | 0 | 13 | 25 |
| 7 | 0 | 0 | 7 | 30 | 4 | 3 | 0 | 21 |
| 8 | 0 | 0 | 6 | 26 | 164 | 156 | 0 | 0 |
| 9 | 0 | 0 | 10 | 46 | 297 | 283 | 0 | 0 |
| 10 | 0 | 0 | 24 | 111 | 349 | 332 | 0 | 0 |
| 11 | 0 | 0 | 43 | 196 | 371 | 354 | 0 | 0 |
| 12 | 0 | 0 | 51 | 235 | 391 | 372 | 0 | 0 |
| 13 | 0 | 0 | 55 | 252 | 399 | 380 | 0 | 0 |
| 14 | 0 | 0 | 59 | 269 | 405 | 386 | 0 | 0 |
| 15 | 0 | 0 | 61 | 280 | 422 | 402 | 0 | 0 |
| 16 | 0 | 0 | 65 | 298 | 430 | 409 | 0 | 0 |
| 17 | 0 | 0 | 62 | 284 | 423 | 403 | 0 | 0 |
| 18 | 0 | 0 | 54 | 249 | 340 | 324 | 0 | 0 |
| 19 | 0 | 0 | 54 | 248 | 204 | 194 | 0 | 0 |
| 20 | 0 | 0 | 32 | 148 | 106 | 101 | 0 | 0 |
| 21 | 0 | 0 | 16 | 72 | 60 | 57 | 0 | 0 |
| 22 | 0 | 0 | 10 | 45 | 39 | 37 | 0 | 0 |
| 23 | 0 | 0 | 6 | 27 | 38 | 36 | 0 | 0 |
| 24 | 0 | 0 | 4 | 20 | 35 | 34 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 79 | 32 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 116 | 77 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

Table 6-42 (continued)

| | | | |
|---|---|---|---|
| 17 | [104%] | 130 | 109 |
| 18 | [85%] | 109 | 67 |
| 19 | [104%] | 130 | 109 |
| 20 | [104%] | 129 | 109 |
| 21 | [85%] | 103 | 63 |
| 22 | [68%] | 90 | 43 |
| 23 | [68%] | 88 | 42 |
| 24 | [68%] | 82 | 40 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 55 | 55 | 0 |
| 10 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 11 | [100%] | 48 | 48 | 48 |
| 12 | [100%] | 55 | 50 | 50 |
| 13 | [100%] | 55 | 52 | 52 |
| 14 | [100%] | 55 | 55 | 51 |
| 15 | [100%] | 52 | 52 | 52 |
| 16 | [100%] | 53 | 53 | 53 |
| 17 | [100%] | 52 | 52 | 52 |
| 18 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 19 | [100%] | 48 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 109 | 109 | 0 |
| 10 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 11 | [100%] | 96 | 96 | 96 |
| 12 | [100%] | 109 | 100 | 100 |
| 13 | [100%] | 109 | 103 | 103 |
| 14 | [100%] | 109 | 109 | 103 |
| 15 | [100%] | 103 | 103 | 103 |
| 16 | [100%] | 106 | 106 | 106 |
| 17 | [100%] | 104 | 104 | 104 |
| 18 | [100%]. [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 19 | [100%] | 96 | 0 | 0 |

### E.3.9 *Hourly LCA Optimization Model* for min AP in a day in September

**Table 6-43: Supply from the energy systems in an average day in September (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 16 | 15 | 2 | 10 |
| 2 | 0 | 0 | 0 | 0 | 12 | 12 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 10 | 9 | 9 | 15 |
| 4 | 0 | 0 | 0 | 0 | 7 | 7 | 12 | 15 |
| 5 | 0 | 0 | 0 | 0 | 6 | 5 | 16 | 13 |
| 6 | 0 | 0 | 0 | 0 | 4 | 4 | 19 | 11 |
| 7 | 0 | 0 | 0 | 0 | 8 | 7 | 9 | 5 |
| 8 | 0 | 0 | 0 | 0 | 79 | 75 | 0 | 64 |
| 9 | 0 | 0 | 0 | 0 | 173 | 165 | 0 | 88 |
| 10 | 0 | 0 | 3 | 15 | 269 | 256 | 0 | 0 |
| 11 | 0 | 0 | 16 | 72 | 308 | 293 | 0 | 0 |
| 12 | 0 | 0 | 23 | 107 | 323 | 308 | 0 | 0 |
| 13 | 0 | 0 | 26 | 121 | 347 | 330 | 0 | 0 |
| 14 | 0 | 0 | 31 | 143 | 350 | 334 | 0 | 0 |
| 15 | 0 | 0 | 36 | 166 | 357 | 340 | 0 | 0 |
| 16 | 0 | 0 | 40 | 184 | 357 | 340 | 0 | 0 |
| 17 | 0 | 0 | 34 | 154 | 350 | 333 | 0 | 0 |
| 18 | 0 | 0 | 29 | 131 | 258 | 246 | 0 | 0 |
| 19 | 0 | 0 | 25 | 116 | 141 | 134 | 0 | 0 |
| 20 | 0 | 0 | 14 | 63 | 58 | 56 | 0 | 0 |
| 21 | 0 | 0 | 6 | 26 | 39 | 37 | 0 | 0 |
| 22 | 0 | 0 | 2 | 8 | 28 | 26 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 25 | 24 | 0 | 3 |
| 24 | 0 | 0 | 0 | 0 | 20 | 19 | 0 | 6 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 118 | 79 |
| 9 | [93%] | 114 | 76 |
| 10 | [93%] | 120 | 80 |
| 11 | [104%] | 130 | 109 |
| 12 | [104%] | 130 | 109 |
| 13 | [93%] | 112 | 75 |
| 14 | [93%] | 117 | 78 |

Table 6-43 (continued)

| | | | |
|---|---|---|---|
| 15 | [93%] | 120 | 80 |
| 16 | [85%] | 111 | 68 |
| 17 | [93%] | 120 | 80 |
| 18 | [85%] | 111 | 68 |
| 19 | [85%] | 105 | 65 |
| 20 | [85%] | 104 | 64 |
| 21 | [68%] | 89 | 43 |
| 22 | [62%] | 79 | 32 |
| 23 | [62%] | 80 | 33 |
| 24 | [62%] | 76 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [75%] | 34 | 0 | 0 |
| 9 | [100%] | 48 | 48 | 0 |
| 10 | [100%] | 48 | 48 | 0 |
| 11 | [100%] | 50 | 50 | 0 |
| 12 | [100%] | 54 | 54 | 0 |
| 13 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 14 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 15 | [100%], [75%] | 49 [100%] | 49 [100%] | 34 [75%] |
| 16 | [100%] | 48 | 48 | 48 |
| 17 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 18 | [100%] | 48 | 48 | 0 |
| 19 | [75%] | 34 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [75%] | 79 | 0 | 0 |
| 9 | [100%] | 96 | 96 | 0 |
| 10 | [100%] | 96 | 96 | 0 |
| 11 | [100%] | 99 | 99 | 0 |
| 12 | [100%] | 108 | 108 | 0 |
| 13 | [100%], [75%] | 96 | 96 | 79 [75%] |
| 14 | [100%], [75%] | 96 | 96 | 79 [75%] |
| 15 | [100%], [75%] | 98 | 98 | 79 [75%] |
| 16 | [100%] | 96 | 96 | 96 |
| 17 | [100%], [75%] | 96 | 96 | 79 [75%] |
| 18 | [100%] | 96 | 96 | 0 |
| 19 | [75%] | 79 | 0 | 0 |

## E.3.10 *Hourly LCA Optimization Model* for min AP in a day in October

**Table 6-44: Supply from the energy systems in an average day in October (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 4 | 0 | 0 | 0 | 0 | 17 | 0 |
| 2 | 0 | 37 | 0 | 0 | 0 | 0 | 3 | 0 |
| 3 | 0 | 52 | 0 | 0 | 0 | 0 | 6 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 46 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 54 | 0 |
| 7 | 0 | 1 | 0 | 0 | 0 | 0 | 43 | 0 |
| 8 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 48 |
| 9 | 0 | 0 | 0 | 0 | 24 | 23 | 0 | 218 |
| 10 | 0 | 0 | 0 | 0 | 107 | 102 | 0 | 153 |
| 11 | 0 | 0 | 0 | 0 | 208 | 198 | 0 | 58 |
| 12 | 0 | 0 | 1 | 5 | 275 | 262 | 0 | 0 |
| 13 | 0 | 0 | 7 | 32 | 289 | 275 | 0 | 0 |
| 14 | 0 | 0 | 10 | 45 | 307 | 292 | 0 | 0 |
| 15 | 0 | 0 | 14 | 64 | 312 | 297 | 0 | 0 |
| 16 | 0 | 0 | 13 | 60 | 312 | 298 | 0 | 0 |
| 17 | 0 | 0 | 8 | 35 | 289 | 275 | 0 | 0 |
| 18 | 0 | 0 | 3 | 12 | 212 | 202 | 0 | 0 |
| 19 | 0 | 0 | 2 | 11 | 59 | 56 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 17 |
| 21 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 22 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 16 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 24 | 0 | 5 | 0 | 0 | 0 | 0 | 4 | 0 |
| | **Part Load** | | | **P_SOFC** | | | **H_SOFC** | |
| 1 | [78%] | | | 92 | | | 51 | |
| 2 | [62%] | | | 75 | | | 31 | |
| 3 | [62%] | | | 75 | | | 31 | |
| 4 | [62%] | | | 75 | | | 31 | |
| 5 | [62%] | | | 75 | | | 31 | |
| 6 | [62%] | | | 75 | | | 31 | |
| 7 | [62%] | | | 75 | | | 31 | |
| 8 | [85%] | | | 108 | | | 66 | |
| 9 | [93%] | | | 119 | | | 79 | |
| 10 | [93%] | | | 120 | | | 80 | |
| 11 | [93%] | | | 120 | | | 80 | |
| 12 | [93%] | | | 120 | | | 80 | |
| 13 | [93%] | | | 120 | | | 80 | |
| 14 | [104%] | | | 130 | | | 109 | |
| 15 | [100%] | | | 127 | | | 99 | |
| 16 | [104%] | | | 130 | | | 109 | |

| Table 6-44 (continued) | | | |
|---|---|---|---|
| 17 | [93%] | 120 | 80 |
| 18 | [104%] | 130 | 109 |
| 19 | [85%] | 109 | 67 |
| 20 | [68%] | 85 | 41 |
| 21 | [62%] | 80 | 33 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [68%] | 82 | 39 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 4 | [50%] | 23 | 0 |
| 5 | [75%] | 34 | 0 |
| 6 | [75%] | 40 | 0 |
| 7 | [75%] | 40 | 0 |
| 8 | [100%] | 48 | 0 |
| 9 | [100%] | 48 | 48 |
| 10 | [100%] | 48 | 48 |
| 11 | [100%] | 49 | 48 |
| 12 | [100%] | 52 | 48 |
| 13 | [100%] | 55 | 51 |
| 14 | [100%] | 50 | 50 |
| 15 | [100%] | 54 | 54 |
| 16 | [100%] | 55 | 48 |
| 17 | [100%] | 55 | 51 |
| 18 | [100%] | 54 | 0 |

**H_MT**

| Hour | MT No. / Percent Load | 1 | 2 |
|---|---|---|---|
| 4 | [50%] | 65 | 0 |
| 5 | [75%] | 79 | 0 |
| 6 | [75%] | 92 | 0 |
| 7 | [75%] | 93 | 0 |
| 8 | [100%] | 96 | 0 |
| 9 | [100%] | 96 | 96 |
| 10 | [100%] | 96 | 96 |
| 11 | [100%] | 97 | 96 |
| 12 | [100%] | 103 | 96 |
| 13 | [100%] | 109 | 101 |
| 14 | [100%] | 99 | 99 |
| 15 | [100%] | 107 | 107 |
| 16 | [100%] | 109 | 96 |
| 17 | [100%] | 109 | 102 |
| 18 | [100%] | 107 | 0 |

### E.3.11 *Hourly LCA Optimization Model* for min AP in a day in November

**Table 6-45: Supply from the energy systems in an average day in November (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 16 | 0 | 0 | 0 | 0 | 72 | 0 |
| 2 | 0 | 24 | 0 | 0 | 0 | 0 | 75 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 88 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 94 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 111 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 0 |
| 8 | 0 | 5 | 0 | 0 | 0 | 0 | 4 | 0 |
| 9 | 0 | 0 | 0 | 0 | 12 | 11 | 0 | 137 |
| 10 | 0 | 0 | 0 | 0 | 40 | 38 | 0 | 163 |
| 11 | 0 | 0 | 0 | 0 | 67 | 63 | 0 | 159 |
| 12 | 0 | 0 | 0 | 0 | 106 | 101 | 0 | 128 |
| 13 | 0 | 0 | 0 | 0 | 137 | 131 | 0 | 100 |
| 14 | 0 | 0 | 0 | 0 | 157 | 149 | 0 | 84 |
| 15 | 0 | 0 | 0 | 0 | 168 | 160 | 0 | 64 |
| 16 | 0 | 0 | 0 | 0 | 141 | 134 | 0 | 78 |
| 17 | 0 | 0 | 0 | 0 | 76 | 73 | 0 | 120 |
| 18 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 78 |
| 19 | 0 | 19 | 0 | 2 | 0 | 0 | 2 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 0 |
| 21 | 0 | 35 | 0 | 0 | 0 | 0 | 29 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 63 | 0 |
| 23 | 0 | 5 | 0 | 0 | 0 | 0 | 66 | 0 |
| 24 | 0 | 20 | 0 | 0 | 0 | 0 | 69 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [62%] | 75 | 31 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [85%] | 109 | 67 |
| 15 | [85%] | 109 | 67 |
| 16 | [85%] | 108 | 66 |

Table 6-45 (continued)

| | | | |
|---|---|---|---|
| 17 | [93%] | 120 | 80 |
| 18 | [93%] | 120 | 80 |
| 19 | [85%] | 102 | 63 |
| 20 | [62%] | 75 | 31 |
| 21 | [62%] | 75 | 31 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | [75%] | 40 | 40 | 0 |
| 2 | [75%] | 40 | 40 | 0 |
| 3 | [75%], [50%] | 35 [75%] | 34 | 21 [50%] |
| 4 | [75%], [50%] | 36 [75%] | 36 [75%] | 21 [50%] |
| 5 | [75%], [50%] | 40 [75%] | 35 [75%] | 21 [50%] |
| 6 | [75%] | 34 | 34 | 34 |
| 7 | [75%], [50%] | 35 [75%] | 35 [75%] | 21 [50%] |
| 8 | [75%] | 40 | 40 | 0 |
| 9 | [100%], [75%] | 50 [100%] | 34 [75%] | 0 |
| 10 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 11 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 12 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 13 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 14 | [100%] | 48 | 48 | 0 |
| 15 | [100%] | 48 | 48 | 0 |
| 16 | [100%] | 48 | 48 | 0 |
| 17 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 18 | [100%] | 48 | 0 | 0 |
| 19 | | 0 | 0 | 0 |
| 20 | [75%] | 38 | 0 | 0 |
| 21 | [75%] | 40 | 0 | 0 |
| 22 | [75%] | 37 | 34 | 0 |
| 23 | [75%] | 40 | 40 | 0 |
| 24 | [75%] | 40 | 40 | 0 |

**H_MT**

| Hour | MT No. / Percent Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | [75%] | 93 | 93 | 0 |
| 2 | [75%] | 93 | 93 | 0 |
| 3 | [75%], [50%] | 81 | 79 | 58 [50%] |
| 4 | [75%], [50%] | 84 | 84 | 58 [50%] |
| 5 | [75%], [50%] | 93 | 82 | 58 [50%] |
| 6 | [75%] | 80 | 80 | 80 |
| 7 | [75%], [50%] | 82 | 82 | 58 [50%] |
| 8 | [100%] | 93 | 93 | 0 |

| Table 6-45 (continued) | | | | |
|---|---|---|---|---|
| 9 | [100%], [75%] | 99 | 79 [75%] | 0 |
| 10 | [100%], [75%] | 97 | 79 [75%] | 0 |
| 11 | [100%], [75%] | 97 | 79 [75%] | 0 |
| 12 | [100%], [75%] | 99 | 79 [75%] | 0 |
| 13 | [100%], [75%] | 99 | 79 [75%] | 0 |
| 14 | [100%] | 96 | 96 | 0 |
| 15 | [100%] | 96 | 96 | 0 |
| 16 | [100%] | 96 | 96 | 0 |
| 17 | [100%], [75%] | 97 | 79 [75%] | 0 |
| 18 | [100%] | 96 | 0 | 0 |
| 20 | [75%] | 88 | 0 | 0 |
| 21 | [75%] | 93 | 0 | 0 |
| 22 | [75%] | 87 | 79 | 0 |
| 23 | [75%] | 93 | 93 | 0 |
| 24 | [75%] | 93 | 93 | 0 |

### E.3.12 *Hourly LCA Optimization Model* for min AP in a day in December

**Table 6-46: Supply from the energy systems in an average day in December (Hourly model: min AP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 136 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 143 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 150 | 0 |
| 4 | 0 | 3 | 0 | 0 | 0 | 0 | 154 | 0 |
| 5 | 0 | 8 | 0 | 0 | 0 | 0 | 157 | 0 |
| 6 | 0 | 15 | 0 | 0 | 0 | 0 | 160 | 0 |
| 7 | 0 | 6 | 0 | 0 | 0 | 0 | 150 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 88 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 5 | 4 | 0 | 78 |
| 11 | 0 | 0 | 0 | 0 | 15 | 15 | 0 | 125 |
| 12 | 0 | 0 | 0 | 0 | 29 | 28 | 0 | 141 |
| 13 | 0 | 0 | 0 | 0 | 57 | 55 | 0 | 124 |
| 14 | 0 | 0 | 0 | 0 | 78 | 75 | 0 | 113 |
| 15 | 0 | 0 | 0 | 0 | 81 | 77 | 0 | 113 |
| 16 | 0 | 0 | 0 | 0 | 52 | 49 | 0 | 126 |
| 17 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 112 |
| 18 | 0 | 0 | 1 | 3 | 3 | 3 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 76 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 101 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 112 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 119 | 0 |

Table 6-46 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 127 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [62%] | 75 | 31 |
| 9 | [100%] | 125 | 97 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 115 | 77 |
| 12 | [93%] | 115 | 77 |
| 13 | [93%] | 115 | 77 |
| 14 | [93%] | 116 | 77 |
| 15 | [93%] | 117 | 78 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 115 | 77 |
| 18 | [104%] | 128 | 107 |
| 19 | [62%] | 75 | 31 |
| 20 | [62%] | 75 | 31 |
| 21 | [62%] | 75 | 31 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 40 | 40 | 35 | 35 | 0 |
| 2 | [75%] | 40 | 40 | 40 | 34 | 0 |
| 3 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 4 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 5 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 6 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 7 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 8 | [75%] | 36 | 34 | 34 | 34 | 34 |
| 9 | [100%], [75%] | 54 [100%] | 34 [75%] | 0 | 0 | 0 |
| 10 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 | 0 |

Table 6-46 (continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| 18 | [100%] | 48 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 36 | 36 | 0 | 0 | 0 |
| 20 | [75%], [50%] | 37 [75%] | 37 [75%] | 21 [50%] | 0 | 0 |
| 21 | [75%], [50%] | 40 [75%] | 39 [75%] | 39 [75%] | 21 [50%] | 0 |
| 22 | [75%] | 36 | 36 | 36 | 0 | 0 |
| 23 | [75%] | 37 | 34 | 34 | 34 | 0 |
| 24 | [75%] | 40 | 35 | 34 | 34 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 93 | 93 | 82 | 82 | 0 |
| 2 | [75%] | 93 | 93 | 93 | 80 | 0 |
| 3 | [75%] | 92 | 92 | 92 | 92 | 0 |
| 4 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 5 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 6 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 7 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 8 | [75%] | 83 | 79 | 79 | 79 | 79 |
| 9 | [100%], [75%] | 108 [100%] | 79 [75%] | 0 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 18 | [100%] | 96 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 84 | 84 | 0 | 0 | 0 |
| 20 | [75%], [50%] | 87 [75%] | 87 [75%] | 58 [50%] | 0 | 0 |
| 21 | [75%], [50%] | 93 [75%] | 91 [75%] | 91 [75%] | 58 [50%] | 0 |
| 22 | [75%] | 83 | 83 | 83 | 0 | 0 |
| 23 | [75%] | 86 | 79 | 79 | 79 | 0 |
| 24 | [75%] | 93 | 82 | 79 | 79 | 0 |

## E.4 AVERAGE ELECTRIC OPTION: MIN TOPP

### E.4.1 *Hourly LCA Optimization Model* for min TOPP in a day in January

**Table 6-47: Supply from the energy systems in an average day in January (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 194 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 202 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 216 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 223 | 0 |
| 5 | 0 | 2 | 0 | 0 | 0 | 0 | 230 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 243 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 222 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 155 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 0 |
| 10 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 50 |
| 11 | 0 | 0 | 0 | 0 | 9 | 8 | 0 | 117 |
| 12 | 0 | 0 | 0 | 0 | 22 | 21 | 0 | 134 |
| 13 | 0 | 0 | 0 | 0 | 35 | 34 | 0 | 139 |
| 14 | 0 | 0 | 0 | 0 | 54 | 51 | 0 | 135 |
| 15 | 0 | 0 | 0 | 0 | 70 | 67 | 0 | 112 |
| 16 | 0 | 0 | 0 | 0 | 63 | 60 | 0 | 92 |
| 17 | 0 | 0 | 0 | 0 | 28 | 27 | 0 | 76 |
| 18 | 0 | 0 | 0 | 2 | 0 | 0 | 19 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 128 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 158 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 186 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 177 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 189 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [78%] | 92 | 51 |
| 4 | [78%] | 92 | 51 |
| 5 | [78%] | 92 | 51 |
| 6 | [85%] | 102 | 63 |
| 7 | [78%] | 92 | 51 |
| 8 | [62%] | 75 | 31 |
| 9 | [62%] | 75 | 31 |

Table 6-47 (continued)

| | | | |
|---|---|---|---|
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 115 | 77 |
| 12 | [93%] | 115 | 77 |
| 13 | [93%] | 115 | 77 |
| 14 | [93%] | 115 | 77 |
| 15 | [93%] | 115 | 77 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 116 | 77 |
| 18 | [78%] | 92 | 51 |
| 19 | [78%] | 92 | 51 |
| 20 | [62%] | 75 | 31 |
| 21 | [78%] | 92 | 51 |
| 22 | [104%] | 128 | 107 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| | Part Load | | | | | |
| 1 | [100%] | 53 | 53 | 53 | 53 | 0 |
| 2 | [100%] | 55 | 54 | 54 | 54 | 0 |
| 3 | [100%] | 55 | 52 | 52 | 52 | 0 |
| 4 | [100%] | 55 | 55 | 55 | 51 | 0 |
| 5 | [100%] | 55 | 55 | 55 | 55 | 0 |
| 6 | [100%] | 55 | 55 | 55 | 55 | 0 |
| 7 | [100%] | 55 | 55 | 55 | 55 | 0 |
| 8 | [100%] | 48 | 48 | 48 | 48 | 48 |
| 9 | [100%] | 55 | 50 | 48 | 0 | 0 |
| 10 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 18 | [100%] | 52 | 52 | 0 | 0 | 0 |
| 19 | [100%] | 55 | 53 | 0 | 0 | 0 |
| 20 | [100%] | 50 | 50 | 50 | 0 | 0 |
| 21 | [100%] | 55 | 53 | 53 | 0 | 0 |
| 22 | [100%] | 55 | 48 | 48 | 0 | 0 |
| 23 | [100%] | 55 | 49 | 49 | 49 | 0 |
| 24 | [100%] | 55 | 52 | 52 | 52 | 0 |

**H_MT**

| Hour | MT No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| | Part Load | | | | | |
| 1 | [100%] | 105 | 105 | 105 | 105 | 0 |

| Table 6-47 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 2 | [100%] | 109 | 107 | 107 | 107 | 0 |
| 3 | [100%] | 109 | 104 | 104 | 104 | 0 |
| 4 | [100%] | 109 | 109 | 109 | 102 | 0 |
| 5 | [100%] | 109 | 109 | 109 | 109 | 0 |
| 6 | [100%] | 109 | 109 | 109 | 109 | 0 |
| 7 | [100%] | 109 | 109 | 109 | 109 | 0 |
| 8 | [100%] | 96 | 96 | 96 | 96 | 96 |
| 9 | [100%] | 109 | 99 | 96 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 18 | [100%] | 104 | 104 | 0 | 0 | 0 |
| 19 | [100%] | 109 | 107 | 0 | 0 | 0 |
| 20 | [100%] | 100 | 100 | 100 | 0 | 0 |
| 21 | [100%] | 109 | 106 | 106 | 0 | 0 |
| 22 | [100%] | 109 | 96 | 96 | 0 | 0 |
| 23 | [100%] | 109 | 97 | 97 | 97 | 0 |
| 24 | [100%] | 109 | 103 | 103 | 103 | 0 |

### E.4.2 *Hourly LCA Optimization Model* for min TOPP in a day in February

**Table 6-48: Supply from the energy systems in an average day in February (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 0 | 0 | 0 | 167 | 0 |
| 2 | 0 | 1 | 0 | 0 | 0 | 0 | 181 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 193 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 187 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 195 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 203 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 186 | 0 |
| 8 | 0 | 8 | 0 | 0 | 0 | 0 | 99 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 36 |
| 10 | 0 | 0 | 0 | 0 | 21 | 20 | 0 | 113 |
| 11 | 0 | 0 | 0 | 0 | 41 | 39 | 0 | 135 |
| 12 | 0 | 0 | 0 | 0 | 64 | 61 | 0 | 139 |
| 13 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 138 |
| 14 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 129 |
| 15 | 0 | 0 | 0 | 0 | 121 | 116 | 0 | 101 |

Table 6-48 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 16 | 0 | 0 | 0 | 0 | 120 | 114 | 0 | 87 |
| 17 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 95 |
| 18 | 0 | 0 | 0 | 0 | 27 | 26 | 0 | 43 |
| 19 | 0 | 0 | 0 | 1 | 0 | 0 | 28 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 78 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 92 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 134 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 132 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 136 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [85%] | 102 | 63 |
| 3 | [104%] | 128 | 107 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [78%] | 92 | 51 |
| 9 | [93%] | 116 | 77 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 116 | 77 |
| 12 | [93%] | 116 | 77 |
| 13 | [93%] | 116 | 77 |
| 14 | [93%] | 116 | 77 |
| 15 | [93%] | 116 | 77 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 116 | 77 |
| 18 | [100%] | 127 | 99 |
| 19 | [68%] | 82 | 93 |
| 20 | [100%] | 121 | 93 |
| 21 | [62%] | 75 | 31 |
| 22 | [100%] | 121 | 93 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | [100%] | 55 | 55 | 55 | 0 |
| 2 | [100%] | 55 | 55 | 55 | 0 |
| 3 | [100%] | 50 | 50 | 50 | 0 |
| 4 | [100%] | 48 | 48 | 48 | 48 |
| 5 | [100%] | 50 | 50 | 50 | 50 |
| 6 | [100%] | 55 | 50 | 50 | 50 |
| 7 | [100%] | 52 | 48 | 48 | 48 |
| 8 | [100%] | 55 | 55 | 55 | 0 |
| 9 | [100%] | 48 | 48 | 0 | 0 |

| Table 6-48 (continued) | | | | | |
|---|---|---|---|---|---|
| 10 | [100%] | 48 | 48 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 |
| 18 | [100%] | 49 | 0 | 0 | 0 |
| 19 | [100%] | 52 | 0 | 0 | 0 |
| 20 | [100%] | 49 | 0 | 0 | 0 |
| 21 | [100%] | 55 | 51 | 0 | 0 |
| 22 | [100%] | 51 | 51 | 0 | 0 |
| 23 | [100%] | 54 | 48 | 48 | 0 |
| 24 | [100%] | 55 | 49 | 49 | 0 |
| | | | **H_MT** | | |
| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 |
| 1 | [100%] | 109 | 109 | 109 | 0 |
| 2 | [100%] | 109 | 109 | 109 | 0 |
| 3 | [100%] | 99 | 99 | 99 | 0 |
| 4 | [100%] | 96 | 96 | 96 | 96 |
| 5 | [100%] | 99 | 99 | 99 | 99 |
| 6 | [100%] | 109 | 99 | 99 | 99 |
| 7 | [100%] | 103 | 96 | 96 | 96 |
| 8 | [100%] | 109 | 109 | 109 | 0 |
| 9 | [100%] | 96 | 96 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 |
| 18 | [100%] | 97 | 0 | 0 | 0 |
| 19 | [100%] | 104 | 0 | 0 | 0 |
| 20 | [100%] | 98 | 0 | 0 | 0 |
| 21 | [100%] | 109 | 102 | 0 | 0 |
| 22 | [100%] | 101 | 101 | 0 | 0 |
| 23 | [100%] | 108 | 96 | 96 | 0 |
| 24 | [100%] | 109 | 97 | 97 | 0 |

## E.4.3 *Hourly LCA Optimization Model* for min TOPP in a day in March

**Table 6-49: Supply from the energy systems in an average day in March (Hourly model: min TOPP)**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 98 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 114 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 123 | 0 |
| 4 | 0 | 2 | 0 | 0 | 0 | 0 | 138 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 149 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 157 | 0 |
| 7 | 0 | 5 | 0 | 0 | 0 | 0 | 124 | 0 |
| 8 | 0 | 0 | 0 | 1 | 0 | 0 | 25 | 0 |
| 9 | 0 | 0 | 0 | 0 | 35 | 33 | 0 | 108 |
| 10 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 105 |
| 11 | 0 | 0 | 0 | 0 | 131 | 124 | 0 | 87 |
| 12 | 0 | 0 | 0 | 0 | 156 | 149 | 0 | 72 |
| 13 | 0 | 0 | 0 | 0 | 178 | 170 | 0 | 61 |
| 14 | 0 | 0 | 0 | 0 | 209 | 199 | 0 | 36 |
| 15 | 0 | 0 | 0 | 0 | 222 | 211 | 0 | 21 |
| 16 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 13 |
| 17 | 0 | 0 | 0 | 0 | 180 | 171 | 0 | 44 |
| 18 | 0 | 0 | 0 | 0 | 102 | 97 | 0 | 25 |
| 19 | 0 | 1 | 5 | 25 | 0 | 0 | 0 | 0 |
| 20 | 0 | 4 | 2 | 8 | 0 | 0 | 32 | 0 |
| 21 | 0 | 0 | 1 | 3 | 0 | 0 | 41 | 0 |
| 22 | 0 | 0 | 0 | 1 | 0 | 0 | 80 | 0 |
| 23 | 0 | 0 | 0 | 1 | 0 | 0 | 90 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 86 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [78%] | 92 | 51 |
| 3 | [78%] | 92 | 51 |
| 4 | [85%] | 102 | 63 |
| 5 | [100%] | 121 | 93 |
| 6 | [104%] | 128 | 107 |
| 7 | [78%] | 92 | 51 |
| 8 | [62%] | 75 | 31 |
| 9 | [93%] | 115 | 77 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 117 | 78 |
| 12 | [93%] | 118 | 79 |
| 13 | [93%] | 118 | 79 |
| 14 | [93%] | 119 | 79 |
| 15 | [93%] | 119 | 79 |
| 16 | [93%] | 119 | 79 |

| Table 6-49 (continued) | | | |
|---|---|---|---|
| 17 | [93%] | 118 | 79 |
| 18 | [100%] | 127 | 99 |
| 19 | [85%] | 109 | 67 |
| 20 | [100%] | 121 | 93 |
| 21 | [62%] | 75 | 31 |
| 22 | [93%] | 111 | 74 |
| 23 | [104%] | 128 | 107 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [100%] | 55 | 51 |
| 2 | [100%] | 54 | 48 |
| 3 | [100%] | 55 | 54 |
| 4 | [100%] | 55 | 55 |
| 5 | [100%] | 50 | 50 |
| 6 | [100%] | 49 | 49 |
| 7 | [100%] | 55 | 55 |
| 8 | [100%] | 55 | 50 |
| 9 | [100%] | 48 | 48 |
| 10 | [100%] | 48 | 48 |
| 11 | [100%] | 48 | 48 |
| 12 | [100%] | 48 | 48 |
| 13 | [100%] | 48 | 48 |
| 14 | [100%] | 48 | 48 |
| 15 | [100%] | 48 | 48 |
| 16 | [100%] | 48 | 48 |
| 17 | [100%] | 48 | 48 |
| 18 | [100%] | 49 | 0 |
| 19 | [100%] | 0 | 0 |
| 20 | [100%] | 0 | 0 |
| 21 | [100%] | 52 | 0 |
| 22 | [100%] | 53 | 0 |
| 23 | [100%] | 50 | 0 |
| 24 | [100%] | 49 | 48 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [100%] | 109 | 101 |
| 2 | [100%] | 107 | 96 |
| 3 | [100%] | 109 | 108 |
| 4 | [100%] | 109 | 109 |
| 5 | [100%] | 99 | 99 |
| 6 | [100%] | 97 | 97 |
| 7 | [100%] | 109 | 109 |
| 8 | [100%] | 109 | 99 |
| 9 | [100%] | 96 | 96 |

| Table 6-49 (continued) | | | |
|---|---|---|---|
| 10 | [100%] | 96 | 96 |
| 11 | [100%] | 96 | 96 |
| 12 | [100%] | 96 | 96 |
| 13 | [100%] | 96 | 96 |
| 14 | [100%] | 96 | 96 |
| 15 | [100%] | 96 | 96 |
| 16 | [100%] | 96 | 96 |
| 17 | [100%] | 96 | 96 |
| 18 | [100%] | 97 | 0 |
| 19 | [100%] | 0 | 0 |
| 20 | [100%] | 0 | 0 |
| 21 | [100%] | 104 | 0 |
| 22 | [100%] | 105 | 0 |
| 23 | [100%] | 99 | 0 |
| 24 | [100%] | 97 | 96 |

### E.4.4 *Hourly LCA Optimization Model* for min TOPP in a day in April

**Table 6-50: Supply from the energy systems in an average day in April (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 0 | 0 | 0 | 0 | 17 | 0 |
| 2 | 0 | 1 | 0 | 0 | 0 | 0 | 31 | 0 |
| 3 | 0 | 7 | 0 | 0 | 0 | 0 | 43 | 0 |
| 4 | 0 | 3 | 0 | 0 | 0 | 0 | 55 | 0 |
| 5 | 0 | 5 | 0 | 0 | 0 | 0 | 65 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 64 | 0 |
| 7 | 0 | 2 | 0 | 0 | 0 | 0 | 57 | 0 |
| 8 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 83 |
| 9 | 0 | 0 | 0 | 0 | 45 | 43 | 0 | 205 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 0 | 143 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 0 | 83 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 0 | 34 |
| 13 | 0 | 0 | 0 | 0 | 274 | 261 | 0 | 10 |
| 14 | 0 | 0 | 4 | 21 | 294 | 280 | 0 | 0 |
| 15 | 0 | 0 | 7 | 30 | 310 | 296 | 0 | 0 |
| 16 | 0 | 0 | 8 | 39 | 313 | 298 | 0 | 0 |
| 17 | 0 | 0 | 6 | 28 | 306 | 292 | 0 | 0 |
| 18 | 0 | 0 | 7 | 32 | 239 | 228 | 0 | 0 |
| 19 | 0 | 0 | 14 | 66 | 88 | 84 | 0 | 0 |
| 20 | 0 | 0 | 5 | 21 | 41 | 39 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 8 |
| 22 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 7 |
| 23 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 7 |

Table 6-50 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 0 | 2 | 0 | 0 | 0 | 0 | 14 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [85%] | 102 | 63 |
| 3 | [93%] | 111 | 74 |
| 4 | [100%] | 121 | 93 |
| 5 | [104%] | 128 | 107 |
| 6 | [62%] | 75 | 31 |
| 7 | [104%] | 128 | 107 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |
| 17 | [104%] | 130 | 109 |
| 18 | [78%] | 96 | 54 |
| 19 | [100%] | 127 | 99 |
| 20 | [78%] | 95 | 53 |
| 21 | [68%] | 82 | 39 |
| 22 | [62%] | 76 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [100%] | 0 | 0 |
| 2 | [100%] | 0 | 0 |
| 3 | [100%] | 0 | 0 |
| 4 | [100%] | 0 | 0 |
| 5 | [100%] | 0 | 0 |
| 6 | [100%] | 49 | 0 |
| 7 | [100%] | 0 | 0 |
| 8 | [100%] | 49 | 0 |
| 9 | [100%] | 52 | 48 |
| 10 | [100%] | 53 | 48 |
| 11 | [100%] | 54 | 48 |
| 12 | [100%] | 51 | 51 |
| 13 | [100%] | 55 | 49 |
| 14 | [100%] | 55 | 53 |
| 15 | [100%] | 51 | 51 |
| 16 | [100%] | 52 | 52 |
| 17 | [100%] | 50 | 50 |

| Table 6-50 (continued) | | | |
|---|---|---|---|
| 18 | [100%] | 48 | 48 |
| 19 | [100%] | 0 | 0 |
| 20 | [100%] | 0 | 0 |
| 21 | [100%] | 0 | 0 |
| 22 | [100%] | 0 | 0 |
| 23 | [100%] | 0 | 0 |
| 24 | [100%] | 0 | 0 |
| | | **H_MT** | |
| Hour | MT No. | 1 | 2 |
| | Part Load | | |
| 1 | [100%] | 0 | 0 |
| 2 | [100%] | 0 | 0 |
| 3 | [100%] | 0 | 0 |
| 4 | [100%] | 0 | 0 |
| 5 | [100%] | 0 | 0 |
| 6 | [100%] | 98 | 0 |
| 7 | [100%] | 0 | 0 |
| 8 | [100%] | 98 | 0 |
| 9 | [100%] | 103 | 96 |
| 10 | [100%] | 105 | 96 |
| 11 | [100%] | 107 | 96 |
| 12 | [100%] | 102 | 102 |
| 13 | [100%] | 109 | 97 |
| 14 | [100%] | 109 | 106 |
| 15 | [100%] | 101 | 101 |
| 16 | [100%] | 103 | 103 |
| 17 | [100%] | 100 | 100 |
| 18 | [100%] | 96 | 96 |
| 19 | [100%] | 0 | 0 |
| 20 | [100%] | 0 | 0 |
| 21 | [100%] | 0 | 0 |
| 22 | [100%] | 0 | 0 |
| 23 | [100%] | 0 | 0 |
| 24 | [100%] | 0 | 0 |

### E.4.5 *Hourly LCA Optimization Model* for min TOPP in a day in May

**Table 6-51: Supply from the energy systems in an average day in May (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 7 | 7 | 3 | 15 |
| 2 | 0 | 0 | 0 | 0 | 5 | 5 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 3 | 3 | 9 | 11 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 12 | 8 |
| 5 | 0 | 0 | 0 | 1 | 0 | 0 | 15 | 6 |
| Table 6-51 (continued) | | | | | | | | |
| 6 | 0 | 0 | 0 | 1 | 0 | 0 | 18 | 0 |
| 7 | 0 | 0 | 0 | 0 | 7 | 7 | 8 | 3 |
| 8 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 82 |
| 9 | 0 | 0 | 0 | 0 | 163 | 155 | 0 | 104 |
| 10 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 18 |
| 11 | 0 | 0 | 8 | 37 | 293 | 279 | 0 | 0 |
| 12 | 0 | 0 | 12 | 56 | 313 | 298 | 0 | 0 |
| 13 | 0 | 0 | 15 | 69 | 320 | 305 | 0 | 0 |
| 14 | 0 | 0 | 18 | 82 | 328 | 312 | 0 | 0 |
| 15 | 0 | 0 | 19 | 88 | 341 | 325 | 0 | 0 |
| 16 | 0 | 0 | 22 | 101 | 342 | 326 | 0 | 0 |
| 17 | 0 | 3 | 19 | 86 | 329 | 314 | 0 | 0 |
| 18 | 0 | 0 | 23 | 104 | 257 | 245 | 0 | 0 |
| 19 | 0 | 0 | 26 | 121 | 145 | 138 | 0 | 0 |
| 20 | 0 | 0 | 18 | 82 | 65 | 62 | 0 | 4 |
| 21 | 0 | 0 | 4 | 17 | 37 | 36 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 23 | 22 | 0 | 4 |
| 23 | 0 | 0 | 0 | 0 | 15 | 14 | 0 | 12 |
| 24 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 16 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 109 | 67 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [104%] | 130 | 109 |

Table 6-51 (continued)

| | | | |
|---|---|---|---|
| 13 | [104%] | 130 | 109 |
| 14 | [104%] | 130 | 109 |
| 15 | [78%] | 97 | 54 |
| 16 | [78%] | 100 | 56 |
| 17 | [104%] | 130 | 109 |
| 18 | [85%] | 110 | 67 |
| 19 | [78%] | 96 | 54 |
| 20 | [93%] | 120 | 80 |
| 21 | [68%] | 87 | 42 |
| 22 | [62%] | 77 | 32 |
| 23 | [62%] | 79 | 33 |
| 24 | [62%] | 76 | 31 |

**P_MT**

| Hour | MT No. | 1 | 2 | 3 |
|---|---|---|---|---|
| | Part Load | | | |
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 50 | 48 | 0 |
| 10 | [100%] | 51 | 48 | 0 |
| 11 | [100%] | 55 | 53 | 0 |
| 12 | [100%] | 52 | 52 | 0 |
| 13 | [100%] | 53 | 53 | 0 |
| 14 | [100%] | 55 | 55 | 0 |
| 15 | [100%] | 48 | 48 | 48 |
| 16 | [100%] | 48 | 48 | 48 |
| 17 | [100%] | 55 | 55 | 0 |
| 18 | [100%] | 48 | 48 | 0 |
| 19 | [100%] | 48 | 0 | 0 |

**H_MT**

| Hour | MT No. | 1 | 2 | 3 |
|---|---|---|---|---|
| | Part Load | | | |
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 99 | 96 | 0 |
| 10 | [100%] | 101 | 96 | 0 |
| 11 | [100%] | 109 | 105 | 0 |
| 12 | [100%] | 103 | 103 | 0 |
| 13 | [100%] | 106 | 106 | 0 |
| 14 | [100%] | 109 | 109 | 0 |
| 15 | [100%] | 96 | 96 | 96 |
| 16 | [100%] | 96 | 96 | 96 |
| 17 | [100%] | 109 | 109 | 0 |
| 18 | [100%] | 96 | 96 | 0 |
| 19 | [100%] | 96 | 0 | 0 |

## E.4.6 *Hourly LCA Optimization Model* for min TOPP in a day in June

**Table 6-52: Supply from the energy systems in an average day in June (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 26 | 25 | 1 | 0 |
| 2 | 0 | 0 | 0 | 0 | 22 | 21 | 5 | 4 |
| 3 | 0 | 0 | 4 | 19 | 0 | 0 | 4 | 25 |
| 4 | 0 | 0 | 3 | 15 | 0 | 0 | 8 | 25 |
| 5 | 0 | 0 | 2 | 11 | 0 | 0 | 13 | 24 |
| 6 | 0 | 0 | 0 | 0 | 9 | 9 | 19 | 14 |
| 7 | 0 | 0 | 7 | 30 | 14 | 14 | 0 | 11 |
| 8 | 0 | 0 | 6 | 28 | 156 | 148 | 0 | 0 |
| 9 | 0 | 0 | 7 | 31 | 272 | 259 | 0 | 0 |
| 10 | 0 | 0 | 18 | 84 | 311 | 296 | 0 | 0 |
| 11 | 0 | 0 | 28 | 127 | 343 | 326 | 0 | 0 |
| 12 | 0 | 0 | 34 | 156 | 351 | 334 | 0 | 0 |
| 13 | 0 | 0 | 36 | 163 | 354 | 337 | 0 | 0 |
| 14 | 0 | 0 | 39 | 180 | 356 | 339 | 0 | 0 |
| 15 | 0 | 0 | 41 | 188 | 359 | 342 | 0 | 0 |
| 16 | 0 | 0 | 45 | 208 | 366 | 348 | 0 | 0 |
| 17 | 0 | 0 | 43 | 199 | 364 | 347 | 0 | 0 |
| 18 | 0 | 0 | 45 | 207 | 288 | 274 | 0 | 0 |
| 19 | 0 | 0 | 51 | 232 | 179 | 170 | 0 | 0 |
| 20 | 0 | 7 | 33 | 151 | 113 | 108 | 0 | 0 |
| 21 | 0 | 0 | 15 | 71 | 53 | 51 | 0 | 0 |
| 22 | 0 | 0 | 6 | 27 | 37 | 35 | 0 | 0 |
| 23 | 0 | 0 | 2 | 9 | 36 | 34 | 0 | 0 |
| 24 | 0 | 0 | 1 | 6 | 28 | 26 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [104%] | 130 | 109 |
| 11 | [78%] | 98 | 55 |
| 12 | [85%] | 105 | 64 |
| 13 | [85%] | 107 | 65 |
| 14 | [85%] | 110 | 68 |
| 15 | [85%] | 111 | 68 |
| 16 | [93%] | 117 | 78 |

| Table 6-52 (continued) | | | |
|---|---|---|---|
| 17 | [93%] | 115 | 77 |
| 18 | [93%] | 120 | 80 |
| 19 | [93%] | 120 | 80 |
| 20 | [104%] | 130 | 109 |
| 21 | [78%] | 101 | 57 |
| 22 | [68%] | 85 | 41 |
| 23 | [68%] | 83 | 40 |
| 24 | [62%] | 78 | 32 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 49 | 49 | 0 |
| 10 | [100%] | 53 | 48 | 0 |
| 11 | [100%] | 48 | 48 | 48 |
| 12 | [100%] | 48 | 48 | 48 |
| 13 | [100%] | 48 | 48 | 48 |
| 14 | [100%] | 48 | 48 | 48 |
| 15 | [100%] | 48 | 48 | 48 |
| 16 | [100%] | 48 | 48 | 48 |
| 17 | [100%] | 48 | 48 | 48 |
| 18 | [100%] | 55 | 49 | 0 |
| 19 | [100%] | 50 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 97 | 97 | 0 |
| 10 | [100%] | 106 | 96 | 0 |
| 11 | [100%] | 96 | 96 | 96 |
| 12 | [100%] | 96 | 96 | 96 |
| 13 | [100%] | 96 | 96 | 96 |
| 14 | [100%] | 96 | 96 | 96 |
| 15 | [100%] | 96 | 96 | 96 |
| 16 | [100%] | 96 | 96 | 96 |
| 17 | [100%] | 96 | 96 | 96 |
| 18 | [100%] | 109 | 98 | 0 |
| 19 | [100%] | 100 | 0 | 0 |

### E.4.7 *Hourly LCA Optimization Model* for min TOPP in a day in July

**Table 6-53: Supply from the energy systems in an average day in July (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 7 | 30 | 30 | 29 | 0 | 4 |
| 2 | 0 | 0 | 6 | 25 | 27 | 25 | 0 | 0 |
| 3 | 0 | 0 | 7 | 30 | 15 | 15 | 0 | 10 |
| 4 | 0 | 0 | 8 | 38 | 0 | 0 | 2 | 25 |
| 5 | 0 | 0 | 7 | 31 | 0 | 0 | 8 | 25 |
| 6 | 0 | 0 | 6 | 27 | 0 | 0 | 12 | 25 |
| 7 | 0 | 0 | 8 | 37 | 27 | 26 | 0 | 0 |
| 8 | 0 | 0 | 13 | 61 | 175 | 167 | 0 | 0 |
| 9 | 0 | 0 | 13 | 59 | 313 | 298 | 0 | 0 |
| 10 | 0 | 0 | 28 | 130 | 352 | 336 | 0 | 0 |
| 11 | 0 | 0 | 44 | 201 | 374 | 356 | 0 | 0 |
| 12 | 0 | 0 | 55 | 252 | 396 | 377 | 0 | 0 |
| 13 | 0 | 0 | 60 | 275 | 408 | 388 | 0 | 0 |
| 14 | 0 | 1 | 62 | 284 | 414 | 394 | 0 | 0 |
| 15 | 0 | 0 | 65 | 300 | 429 | 409 | 0 | 0 |
| 16 | 0 | 0 | 70 | 322 | 440 | 419 | 0 | 0 |
| 17 | 0 | 0 | 69 | 318 | 439 | 418 | 0 | 0 |
| 18 | 0 | 0 | 67 | 307 | 357 | 340 | 0 | 0 |
| 19 | 0 | 0 | 67 | 305 | 247 | 235 | 0 | 0 |
| 20 | 0 | 0 | 45 | 208 | 150 | 143 | 0 | 0 |
| 21 | 0 | 0 | 26 | 118 | 75 | 71 | 0 | 0 |
| 22 | 0 | 0 | 15 | 69 | 51 | 48 | 0 | 0 |
| 23 | 0 | 0 | 9 | 43 | 48 | 46 | 0 | 0 |
| 24 | 0 | 0 | 8 | 36 | 38 | 36 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [68%] | 82 | 39 |
| 2 | [62%] | 77 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 77 | 32 |
| 8 | [93%] | 120 | 80 |
| 9 | [104%] | 130 | 109 |
| 10 | [85%] | 105 | 65 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |

Table 6-53 (continued)

| | | | |
|---|---|---|---|
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |
| 17 | [104%] | 130 | 109 |
| 18 | [85%] | 109 | 67 |
| 19 | [78%] | 99 | 55 |
| 20 | [78%] | 99 | 56 |
| 21 | [93%] | 116 | 77 |
| 22 | [78%] | 97 | 54 |
| 23 | [78%] | 92 | 52 |
| 24 | [68%] | 87 | 42 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 52 | 0 | 0 |
| 9 | [100%] | 51 | 51 | 0 |
| 10 | [100%] | 48 | 48 | 48 |
| 11 | [100%] | 49 | 49 | 49 |
| 12 | [100%] | 55 | 55 | 48 |
| 13 | [100%] | 55 | 54 | 54 |
| 14 | [100%] | 55 | 55 | 55 |
| 15 | [100%] | 55 | 52 | 52 |
| 16 | [100%] | 55 | 55 | 54 |
| 17 | [100%] | 54 | 54 | 54 |
| 18 | [100%] | 48 | 48 | 48 |
| 19 | [100%] | 48 | 48 | 0 |
| 20 | [100%] | 48 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 103 | 0 | 0 |
| 9 | [100%] | 102 | 102 | 0 |
| 10 | [100%] | 96 | 96 | 96 |
| 11 | [100%] | 97 | 97 | 97 |
| 12 | [100%] | 109 | 109 | 96 |
| 13 | [100%] | 109 | 107 | 107 |
| 14 | [100%] | 109 | 109 | 109 |
| 15 | [100%] | 109 | 103 | 103 |
| 16 | [100%] | 109 | 109 | 108 |
| 17 | [100%] | 108 | 108 | 108 |
| 18 | [100%] | 96 | 96 | 96 |
| 19 | [100%] | 96 | 96 | 0 |
| 20 | [100%] | 96 | 0 | 0 |

## E.4.8 *Hourly LCA Optimization Model* for min TOPP in a day in August

**Table 6-54: Supply from the energy systems in an average day in August (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 5 | 21 | 28 | 26 | 0 | 0 |
| 2 | 0 | 0 | 4 | 16 | 24 | 23 | 0 | 2 |
| 3 | 0 | 0 | 2 | 8 | 26 | 25 | 6 | 0 |
| 4 | 0 | 0 | 6 | 29 | 0 | 0 | 4 | 25 |
| 5 | 0 | 0 | 5 | 25 | 0 | 0 | 9 | 25 |
| 6 | 0 | 0 | 5 | 22 | 0 | 0 | 13 | 25 |
| 7 | 0 | 0 | 7 | 30 | 4 | 3 | 0 | 21 |
| 8 | 0 | 0 | 6 | 26 | 164 | 156 | 0 | 0 |
| 9 | 0 | 0 | 10 | 46 | 297 | 283 | 0 | 0 |
| 10 | 0 | 0 | 25 | 113 | 346 | 329 | 0 | 0 |
| 11 | 0 | 0 | 43 | 196 | 371 | 354 | 0 | 0 |
| 12 | 0 | 0 | 51 | 235 | 391 | 372 | 0 | 0 |
| 13 | 0 | 0 | 55 | 252 | 399 | 380 | 0 | 0 |
| 14 | 0 | 0 | 59 | 269 | 405 | 386 | 0 | 0 |
| 15 | 0 | 0 | 61 | 280 | 422 | 402 | 0 | 0 |
| 16 | 0 | 0 | 65 | 298 | 430 | 409 | 0 | 0 |
| 17 | 0 | 0 | 62 | 284 | 423 | 403 | 0 | 0 |
| 18 | 0 | 7 | 55 | 251 | 337 | 321 | 0 | 0 |
| 19 | 0 | 0 | 54 | 248 | 204 | 194 | 0 | 0 |
| 20 | 0 | 0 | 32 | 148 | 106 | 101 | 0 | 0 |
| 21 | 0 | 0 | 16 | 72 | 60 | 57 | 0 | 0 |
| 22 | 0 | 0 | 10 | 45 | 39 | 37 | 0 | 0 |
| 23 | 0 | 0 | 6 | 27 | 38 | 36 | 0 | 0 |
| 24 | 0 | 0 | 4 | 20 | 35 | 34 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 79 | 32 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 77 | 32 |
| 8 | [93%] | 116 | 77 |
| 9 | [93%] | 120 | 80 |
| 10 | [78%] | 102 | 57 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

Table 6-54 (continued)

| | | | |
|---|---|---|---|
| 17 | [104%] | 130 | 109 |
| 18 | [104%] | 130 | 109 |
| 19 | [104%] | 130 | 109 |
| 20 | [104%] | 129 | 109 |
| 21 | [85%] | 103 | 63 |
| 22 | [68%] | 90 | 43 |
| 23 | [68%] | 88 | 42 |
| 24 | [68%] | 82 | 40 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 55 | 55 | 0 |
| 10 | [100%] | 48 | 48 | 48 |
| 11 | [100%] | 49 | 49 | 48 |
| 12 | [100%] | 55 | 50 | 50 |
| 13 | [100%] | 55 | 52 | 52 |
| 14 | [100%] | 55 | 53 | 53 |
| 15 | [100%] | 52 | 52 | 52 |
| 16 | [100%] | 55 | 52 | 52 |
| 17 | [100%] | 55 | 51 | 51 |
| 18 | [100%] | 55 | 55 | 0 |
| 19 | [100%] | 48 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 109 | 109 | 0 |
| 10 | [100%] | 96 | 96 | 96 |
| 11 | [100%] | 97 | 97 | 96 |
| 12 | [100%] | 109 | 100 | 100 |
| 13 | [100%] | 109 | 103 | 103 |
| 14 | [100%] | 109 | 106 | 106 |
| 15 | [100%] | 103 | 103 | 103 |
| 16 | [100%] | 109 | 104 | 104 |
| 17 | [100%] | 109 | 101 | 101 |
| 18 | [100%] | 109 | 109 | 0 |
| 19 | [100%] | 96 | 0 | 0 |

### E.4.9 *Hourly LCA Optimization Model* for min TOPP in a day in September

**Table 6-55: Supply from the energy systems in an average day in September (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 16 | 15 | 2 | 10 |
| 2 | 0 | 0 | 0 | 0 | 12 | 12 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 10 | 9 | 9 | 15 |
| 4 | 0 | 0 | 0 | 0 | 7 | 7 | 12 | 15 |
| 5 | 0 | 0 | 0 | 0 | 6 | 5 | 16 | 13 |
| 6 | 0 | 0 | 0 | 0 | 4 | 4 | 19 | 11 |
| 7 | 0 | 0 | 0 | 0 | 8 | 7 | 9 | 5 |
| 8 | 0 | 0 | 0 | 0 | 79 | 75 | 0 | 62 |
| 9 | 0 | 0 | 0 | 0 | 173 | 165 | 0 | 88 |
| 10 | 0 | 0 | 3 | 15 | 269 | 256 | 0 | 0 |
| 11 | 0 | 0 | 16 | 72 | 308 | 293 | 0 | 0 |
| 12 | 0 | 0 | 23 | 107 | 323 | 308 | 0 | 0 |
| 13 | 0 | 0 | 27 | 124 | 344 | 327 | 0 | 0 |
| 14 | 0 | 0 | 31 | 141 | 352 | 335 | 0 | 0 |
| 15 | 0 | 0 | 37 | 167 | 355 | 338 | 0 | 0 |
| 16 | 0 | 0 | 40 | 184 | 357 | 340 | 0 | 0 |
| 17 | 0 | 0 | 33 | 153 | 351 | 334 | 0 | 0 |
| 18 | 0 | 0 | 29 | 131 | 258 | 246 | 0 | 0 |
| 19 | 0 | 0 | 26 | 117 | 140 | 133 | 0 | 3 |
| 20 | 0 | 0 | 14 | 63 | 58 | 56 | 0 | 0 |
| 21 | 0 | 0 | 6 | 26 | 39 | 37 | 0 | 0 |
| 22 | 0 | 0 | 2 | 8 | 28 | 26 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 25 | 24 | 0 | 3 |
| 24 | 0 | 0 | 0 | 0 | 20 | 19 | 0 | 6 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [78%] | 102 | 57 |
| 9 | [93%] | 114 | 76 |
| 10 | [93%] | 120 | 80 |
| 11 | [104%] | 130 | 109 |
| 12 | [104%] | 130 | 109 |
| 13 | [78%] | 99 | 55 |
| 14 | [85%] | 103 | 63 |

Table 6-55 (continued)

| | | | |
|---|---|---|---|
| 15 | [85%] | 109 | 67 |
| 16 | [85%] | 111 | 68 |
| 17 | [85%] | 105 | 65 |
| 18 | [85%] | 111 | 68 |
| 19 | [78%] | 92 | 51 |
| 20 | [85%] | 104 | 64 |
| 21 | [68%] | 89 | 43 |
| 22 | [62%] | 79 | 32 |
| 23 | [62%] | 80 | 33 |
| 24 | [62%] | 76 | 31 |

**P_MT**

| Hour | MT No. | 1 | 2 | 3 |
|---|---|---|---|---|
| | Part Load | | | |
| 8 | [100%] | 50 | 0 | 0 |
| 9 | [100%] | 48 | 48 | 0 |
| 10 | [100%] | 48 | 48 | 0 |
| 11 | [100%] | 50 | 50 | 0 |
| 12 | [100%] | 54 | 54 | 0 |
| 13 | [100%] | 48 | 48 | 48 |
| 14 | [100%] | 48 | 48 | 48 |
| 15 | [100%] | 48 | 48 | 48 |
| 16 | [100%] | 48 | 48 | 48 |
| 17 | [100%] | 48 | 48 | 48 |
| 18 | [100%] | 48 | 48 | 0 |
| 19 | [100%] | 48 | 0 | 0 |

**H_MT**

| Hour | MT No. | 1 | 2 | 3 |
|---|---|---|---|---|
| | Part Load | | | |
| 8 | [100%] | 100 | 0 | 0 |
| 9 | [100%] | 96 | 96 | 0 |
| 10 | [100%] | 96 | 96 | 0 |
| 11 | [100%] | 99 | 99 | 0 |
| 12 | [100%] | 108 | 108 | 0 |
| 13 | [100%] | 96 | 96 | 96 |
| 14 | [100%] | 96 | 96 | 96 |
| 15 | [100%] | 96 | 96 | 96 |
| 16 | [100%] | 96 | 96 | 96 |
| 17 | [100%] | 96 | 96 | 96 |
| 18 | [100%] | 96 | 96 | 0 |
| 19 | [100%] | 96 | 0 | 0 |

## E.4.10 *Hourly LCA Optimization Model* for min TOPP in a day in October

**Table 6-56: Supply from the energy systems in an average day in October (Hourly model: min TOPP)**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 4 | 0 | 0 | 0 | 0 | 17 | 0 |
| 2 | 0 | 5 | 0 | 0 | 0 | 0 | 31 | 0 |
| 3 | 0 | 9 | 0 | 0 | 0 | 0 | 43 | 0 |
| 4 | 0 | 3 | 0 | 0 | 0 | 0 | 54 | 0 |
| 5 | 0 | 3 | 0 | 0 | 0 | 0 | 65 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 63 | 3 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 52 | 1 |
| 8 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 48 |
| 9 | 0 | 0 | 0 | 0 | 24 | 23 | 0 | 218 |
| 10 | 0 | 0 | 0 | 0 | 107 | 102 | 0 | 153 |
| 11 | 0 | 0 | 0 | 0 | 208 | 198 | 0 | 58 |
| 12 | 0 | 0 | 1 | 5 | 275 | 262 | 0 | 0 |
| 13 | 0 | 0 | 7 | 32 | 289 | 275 | 0 | 0 |
| 14 | 0 | 0 | 10 | 45 | 307 | 292 | 0 | 0 |
| 15 | 0 | 0 | 13 | 60 | 316 | 301 | 0 | 0 |
| 16 | 0 | 0 | 13 | 60 | 312 | 298 | 0 | 0 |
| 17 | 0 | 0 | 8 | 35 | 289 | 275 | 0 | 0 |
| 18 | 0 | 0 | 3 | 12 | 212 | 202 | 0 | 0 |
| 19 | 0 | 0 | 2 | 11 | 59 | 56 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 17 |
| 21 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 22 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 16 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 24 | 0 | 5 | 0 | 0 | 0 | 0 | 4 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [85%] | 102 | 63 |
| 3 | [93%] | 111 | 74 |
| 4 | [100%] | 121 | 93 |
| 5 | [104%] | 128 | 107 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 108 | 66 |
| 9 | [93%] | 119 | 79 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [104%] | 130 | 109 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

Table 6-56 (continued)

| | | | |
|---|---|---|---|
| 17 | [93%] | 120 | 80 |
| 18 | [104%] | 130 | 109 |
| 19 | [85%] | 109 | 67 |
| 20 | [68%] | 85 | 41 |
| 21 | [62%] | 80 | 33 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [68%] | 82 | 39 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 6 | [100%] | 48 | 0 |
| 7 | [100%] | 48 | 0 |
| 8 | [100%] | 48 | 0 |
| 9 | [100%] | 48 | 48 |
| 10 | [100%] | 48 | 48 |
| 11 | [100%] | 49 | 48 |
| 12 | [100%] | 52 | 48 |
| 13 | [100%] | 55 | 51 |
| 14 | [100%] | 52 | 48 |
| 15 | [100%] | 55 | 49 |
| 16 | [100%] | 55 | 48 |
| 17 | [100%] | 55 | 51 |
| 18 | [100%] | 54 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 6 | [100%] | 96 | 0 |
| 7 | [100%] | 96 | 0 |
| 8 | [100%] | 96 | 0 |
| 9 | [100%] | 96 | 96 |
| 10 | [100%] | 96 | 96 |
| 11 | [100%] | 97 | 96 |
| 12 | [100%] | 103 | 96 |
| 13 | [100%] | 109 | 101 |
| 14 | [100%] | 103 | 96 |
| 15 | [100%] | 109 | 98 |
| 16 | [100%] | 109 | 96 |
| 17 | [100%] | 109 | 102 |
| 18 | [100%] | 107 | 0 |

## E.4.11 *Hourly LCA Optimization Model* for min TOPP in a day in November

**Table 6-57: Supply from the energy systems in an average day in November (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 94 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 101 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 108 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 122 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 128 | 0 |
| 6 | 0 | 1 | 0 | 0 | 0 | 0 | 134 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 117 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 0 |
| 9 | 0 | 0 | 0 | 0 | 12 | 11 | 0 | 136 |
| 10 | 0 | 0 | 0 | 0 | 40 | 38 | 0 | 163 |
| 11 | 0 | 0 | 0 | 0 | 67 | 63 | 0 | 159 |
| 12 | 0 | 0 | 0 | 0 | 106 | 101 | 0 | 127 |
| 13 | 0 | 0 | 0 | 0 | 137 | 131 | 0 | 99 |
| 14 | 0 | 0 | 0 | 0 | 157 | 149 | 0 | 84 |
| 15 | 0 | 0 | 0 | 0 | 168 | 160 | 0 | 64 |
| 16 | 0 | 0 | 0 | 0 | 141 | 134 | 0 | 78 |
| 17 | 0 | 0 | 0 | 0 | 76 | 73 | 0 | 120 |
| 18 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 78 |
| 19 | 0 | 8 | 0 | 2 | 0 | 0 | 11 | 0 |
| 20 | 0 | 12 | 0 | 0 | 0 | 0 | 41 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 61 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 90 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 83 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 93 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [78%] | 92 | 51 |
| 5 | [78%] | 92 | 51 |
| 6 | [78%] | 92 | 51 |
| 7 | [78%] | 92 | 51 |
| 8 | [62%] | 75 | 31 |
| 9 | [85%] | 108 | 66 |
| 10 | [85%] | 107 | 66 |
| 11 | [85%] | 107 | 66 |
| 12 | [85%] | 108 | 66 |
| 13 | [85%] | 108 | 66 |
| 14 | [85%] | 109 | 67 |
| 15 | [85%] | 109 | 67 |
| 16 | [85%] | 108 | 66 |

| Table 6-57 (continued) | | | |
|---|---|---|---|
| 17 | [85%] | 107 | 66 |
| 18 | [93%] | 120 | 80 |
| 19 | [93%] | 111 | 74 |
| 20 | [104%] | 128 | 107 |
| 21 | [62%] | 80 | 33 |
| 22 | [78%] | 92 | 51 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |
| | **P_MT** | | |
| Hour | MT No. | 1 | 2 |
| | Part Load | | |
| 1 | [100%] | 54 | 48 |
| 2 | [100%] | 53 | 53 |
| 3 | [100%] | 55 | 55 |
| 4 | [100%] | 52 | 52 |
| 5 | [100%] | 55 | 52 |
| 6 | [100%] | 55 | 55 |
| 7 | [100%] | 54 | 48 |
| 8 | [100%] | 48 | 48 |
| 9 | [100%] | 48 | 48 |
| 10 | [100%] | 48 | 48 |
| 11 | [100%] | 48 | 48 |
| 12 | [100%] | 48 | 48 |
| 13 | [100%] | 48 | 48 |
| 14 | [100%] | 48 | 48 |
| 15 | [100%] | 48 | 48 |
| 16 | [100%] | 48 | 48 |
| 17 | [100%] | 48 | 48 |
| 18 | [100%] | 48 | 0 |
| 21 | [100%] | 54 | 0 |
| 22 | [100%] | 52 | 0 |
| 23 | [100%] | 48 | 48 |
| 24 | [100%] | 55 | 49 |
| | **H_MT** | | |
| Hour | MT No. | 1 | 2 |
| | Part Load | | |
| 1 | [100%] | 107 | 96 |
| 2 | [100%] | 105 | 105 |
| 3 | [100%] | 109 | 109 |
| 4 | [100%] | 103 | 103 |
| 5 | [100%] | 109 | 104 |
| 6 | [100%] | 109 | 109 |
| 7 | [100%] | 107 | 96 |
| 8 | [100%] | 96 | 96 |
| 9 | [100%] | 96 | 96 |
| 10 | [100%] | 96 | 96 |
| 11 | [100%] | 96 | 96 |

| | | | |
|---|---|---|---|
| 12 | [100%] | 96 | 96 |
| 13 | [100%] | 96 | 96 |
| 14 | [100%] | 96 | 96 |
| 15 | [100%] | 96 | 96 |
| 16 | [100%] | 96 | 96 |
| 17 | [100%] | 96 | 96 |
| 18 | [100%] | 96 | 0 |
| 21 | [100%] | 108 | 0 |
| 22 | [100%] | 104 | 0 |
| 23 | [100%] | 96 | 96 |
| 24 | [100%] | 109 | 97 |

### E.4.12 *Hourly LCA Optimization Model* for min TOPP in a day in December

**Table 6-58: Supply from the energy systems in an average day in December (Hourly model: min TOPP).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 0 | 0 | 0 | 0 | 167 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 180 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 191 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 198 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 190 | 2 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 195 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 195 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 117 | 0 |
| 9 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 5 | 4 | 0 | 78 |
| 11 | 0 | 0 | 0 | 0 | 15 | 15 | 0 | 125 |
| 12 | 0 | 0 | 0 | 0 | 29 | 28 | 0 | 141 |
| 13 | 0 | 0 | 0 | 0 | 57 | 55 | 0 | 124 |
| 14 | 0 | 0 | 0 | 0 | 78 | 75 | 0 | 113 |
| 15 | 0 | 0 | 0 | 0 | 81 | 77 | 0 | 113 |
| 16 | 0 | 0 | 0 | 0 | 52 | 49 | 0 | 126 |
| 17 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 112 |
| 18 | 0 | 0 | 1 | 3 | 3 | 3 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 65 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 104 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 135 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 139 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 143 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 158 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [85%] | 102 | 63 |
| 3 | [104%] | 128 | 107 |

| Table 6-58 (continued) | | | |
|---|---|---|---|
| 4 | [104%] | 128 | 107 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [104%] | 128 | 107 |
| 8 | [62%] | 75 | 31 |
| 9 | [85%] | 103 | 63 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 115 | 77 |
| 12 | [93%] | 115 | 77 |
| 13 | [93%] | 115 | 77 |
| 14 | [93%] | 116 | 77 |
| 15 | [93%] | 117 | 78 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 115 | 77 |
| 18 | [104%] | 128 | 107 |
| 19 | [100%] | 121 | 93 |
| 20 | [78%] | 92 | 51 |
| 21 | [104%] | 128 | 107 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 75 | 31 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | [100%] | 55 | 55 | 55 | 0 |
| 2 | [100%] | 55 | 55 | 55 | 0 |
| 3 | [100%] | 51 | 48 | 48 | 0 |
| 4 | [100%] | 54 | 48 | 48 | 0 |
| 5 | [100%] | 48 | 48 | 48 | 48 |
| 6 | [100%] | 50 | 48 | 48 | 48 |
| 7 | [100%] | 55 | 48 | 48 | 0 |
| 8 | [100%] | 55 | 49 | 49 | 49 |
| 9 | [100%] | 55 | 55 | 0 | 0 |
| 10 | [100%] | 48 | 48 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 |
| 18 | [100%] | 48 | 0 | 0 | 0 |
| 19 | [100%] | 53 | 0 | 0 | 0 |
| 20 | [100%] | 55 | 51 | 0 | 0 |
| 21 | [100%] | 50 | 50 | 0 | 0 |
| 22 | [100%] | 55 | 50 | 50 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| 23 | [100%] | 55 | 54 | 54 | 0 |
| 24 | [100%] | 55 | 51 | 51 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| 1 | [100%] | 109 | 109 | 109 | 0 |
| 2 | [100%] | 109 | 109 | 109 | 0 |
| 3 | [100%] | 101 | 96 | 96 | 0 |
| 4 | [100%] | 108 | 96 | 96 | 0 |
| 5 | [100%] | 96 | 96 | 96 | 96 |
| 6 | [100%] | 100 | 96 | 96 | 96 |
| 7 | [100%] | 109 | 96 | 96 | 0 |
| 8 | [100%] | 109 | 97 | 97 | 97 |
| 9 | [100%] | 109 | 109 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 |
| 18 | [100%] | 96 | 0 | 0 | 0 |
| 19 | [100%] | 105 | 0 | 0 | 0 |
| 20 | [100%] | 109 | 103 | 0 | 0 |
| 21 | [100%] | 99 | 99 | 0 | 0 |
| 22 | [100%] | 109 | 99 | 99 | 0 |
| 23 | [100%] | 109 | 107 | 107 | 0 |
| 24 | [100%] | 109 | 102 | 102 | 0 |

## E.5 AVERAGE ELECTRIC OPTION: MIN $NO_X$

### E.5.1 *Hourly LCA Optimization Model* for min $NO_x$ in a day in January

**Table 6-59: Supply from the energy systems in an average day in January (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 163 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 171 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 177 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 184 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 191 | 0 |
| 6 | 0 | 3 | 0 | 0 | 0 | 0 | 196 | 0 |

Table 6-59 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 182 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 120 | 0 |
| 9 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 50 |
| 11 | 0 | 0 | 0 | 0 | 9 | 8 | 0 | 117 |
| 12 | 0 | 0 | 0 | 0 | 22 | 21 | 0 | 134 |
| 13 | 0 | 0 | 0 | 0 | 35 | 34 | 0 | 139 |
| 14 | 0 | 0 | 0 | 0 | 54 | 51 | 0 | 135 |
| 15 | 0 | 0 | 0 | 0 | 70 | 67 | 0 | 112 |
| 16 | 0 | 0 | 0 | 0 | 63 | 60 | 0 | 92 |
| 17 | 0 | 0 | 0 | 0 | 28 | 27 | 0 | 76 |
| 18 | 0 | 0 | 0 | 2 | 0 | 0 | 13 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 67 | 1 |
| 20 | 0 | 1 | 0 | 0 | 0 | 0 | 114 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 126 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 152 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 148 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 159 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [62%] | 75 | 31 |
| 9 | [78%] | 94 | 53 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 115 | 77 |
| 12 | [93%] | 115 | 77 |
| 13 | [93%] | 115 | 77 |
| 14 | [93%] | 115 | 77 |
| 15 | [93%] | 115 | 77 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 116 | 77 |
| 18 | [93%] | 111 | 74 |
| 19 | [62%] | 75 | 31 |
| 20 | [78%] | 92 | 51 |
| 21 | [62%] | 75 | 31 |
| 22 | [78%] | 92 | 51 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| | Part Load | | | | | | |

| Table 6-59 (continued) | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | [75%] | 40 | 35 | 35 | 35 | 35 | 0 |
| 2 | [75%] | 40 | 36 | 36 | 36 | 36 | 0 |
| 3 | [75%] | 40 | 40 | 38 | 38 | 34 | 0 |
| 4 | [75%] | 40 | 40 | 40 | 40 | 34 | 0 |
| 5 | [75%] | 40 | 40 | 40 | 39 | 39 | 0 |
| 6 | [75%] | 40 | 40 | 40 | 40 | 40 | 0 |
| 7 | [75%] | 40 | 40 | 39 | 39 | 39 | 0 |
| 8 | [75%] | 36 | 34 | 34 | 34 | 34 | 34 |
| 9 | [75%] | 40 | 40 | 40 | 0 | 0 | 0 |
| 10 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 | 0 | 0 |
| 18 | [75%] | 40 | 40 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 34 | 34 | 34 | 0 | 0 | 0 |
| 20 | [75%] | 40 | 40 | 40 | 0 | 0 | 0 |
| 21 | [75%] | 38 | 38 | 38 | 34 | 0 | 0 |
| 22 | [75%] | 40 | 40 | 40 | 34 | 0 | 0 |
| 23 | [75%] | 34 | 34 | 34 | 34 | 34 | 0 |
| 24 | [75%] | 40 | 36 | 36 | 34 | 34 | 0 |
| **H_MT** | | | | | | | |
| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | [75%] | 93 | 82 | 82 | 82 | 82 | 0 |
| 2 | [75%] | 93 | 85 | 85 | 85 | 85 | 0 |
| 3 | [75%] | 93 | 93 | 88 | 88 | 79 | 0 |
| 4 | [75%] | 93 | 93 | 93 | 93 | 79 | 0 |
| 5 | [75%] | 93 | 93 | 93 | 91 | 91 | 0 |
| 6 | [75%] | 93 | 93 | 93 | 93 | 93 | 0 |
| 7 | [75%] | 93 | 93 | 90 | 90 | 90 | 0 |
| 8 | [75%] | 83 | 79 | 79 | 79 | 79 | 79 |
| 9 | [75%] | 93 | 93 | 93 | 0 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 | 0 | 0 |
| 18 | [75%] | 93 | 93 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 79 | 79 | 79 | 0 | 0 | 0 |

| Table 6-59 (continued) | | | | | | | |
|---|---|---|---|---|---|---|---|
| 20 | [75%] | 93 | 93 | 93 | 0 | 0 | 0 |
| 21 | [75%] | 88 | 88 | 88 | 79 | 0 | 0 |
| 22 | [75%] | 93 | 92 | 92 | 79 | 0 | 0 |
| 23 | [75%] | 80 | 80 | 80 | 80 | 80 | 0 |
| 24 | [75%] | 93 | 83 | 83 | 79 | 79 | 0 |

### E.5.2 *Hourly LCA Optimization Model* for min $NO_x$ in a day in February

**Table 6-60: Supply from the energy systems in an average day in February (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 135 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 144 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 151 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 168 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 167 | 1 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 174 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 166 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 70 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 36 |
| 10 | 0 | 0 | 0 | 0 | 21 | 20 | 0 | 113 |
| 11 | 0 | 0 | 0 | 0 | 41 | 39 | 0 | 135 |
| 12 | 0 | 0 | 0 | 0 | 64 | 61 | 0 | 139 |
| 13 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 138 |
| 14 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 129 |
| 15 | 0 | 0 | 0 | 0 | 121 | 116 | 0 | 101 |
| 16 | 0 | 0 | 0 | 0 | 120 | 114 | 0 | 87 |
| 17 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 95 |
| 18 | 0 | 0 | 0 | 0 | 27 | 26 | 0 | 43 |
| 19 | 0 | 0 | 0 | 1 | 0 | 0 | 26 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 52 | 0 |
| 21 | 0 | 5 | 0 | 0 | 0 | 0 | 82 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 118 | 0 |
| 24 | 0 | 5 | 0 | 0 | 0 | 0 | 120 | 0 |
| **Hour** | **Part Load** | | | | **P_SOFC** | | **H_SOFC** | |
| 1 | [62%] | | | | 75 | | 31 | |
| 2 | [62%] | | | | 75 | | 31 | |
| 3 | [62%] | | | | 75 | | 31 | |
| 4 | [78%] | | | | 92 | | 51 | |
| 5 | [62%] | | | | 75 | | 31 | |
| 6 | [62%] | | | | 75 | | 31 | |
| 7 | [78%] | | | | 92 | | 51 | |
| 8 | [62%] | | | | 75 | | 31 | |

Table 6-60 (continued)

| | | | |
|---|---|---|---|
| 9 | [93%] | 116 | 77 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 116 | 77 |
| 12 | [93%] | 116 | 77 |
| 13 | [93%] | 116 | 77 |
| 14 | [93%] | 116 | 77 |
| 15 | [93%] | 116 | 77 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 116 | 77 |
| 18 | [100%] | 127 | 99 |
| 19 | [78%] | 92 | 51 |
| 20 | [62%] | 75 | 31 |
| 21 | [78%] | 92 | 51 |
| 22 | [62%] | 75 | 31 |
| 23 | [78%] | 92 | 51 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 40 | 40 | 35 | 35 | 0 |
| 2 | [75%] | 40 | 38 | 38 | 38 | 0 |
| 3 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 4 | [75%] | 40 | 40 | 38 | 38 | 0 |
| 5 | [75%] | 34 | 34 | 34 | 34 | 34 |
| 6 | [75%] | 35 | 35 | 35 | 35 | 35 |
| 7 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 8 | [75%] | 40 | 40 | 37 | 37 | 0 |
| 9 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 10 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 18 | [100%] | 49 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 39 | 0 | 0 | 0 | 0 |
| 20 | [75%] | 34 | 34 | 0 | 0 | 0 |
| 21 | [75%] | 40 | 40 | 0 | 0 | 0 |
| 22 | [75%] | 40 | 40 | 34 | 0 | 0 |
| 23 | [75%] | 40 | 40 | 40 | 0 | 0 |
| 24 | [75%] | 40 | 40 | 40 | 0 | 0 |

**H_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 93 | 93 | 82 | 82 | 0 |

| Table 6-60 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 2 | [75%] | 93 | 89 | 89 | 89 | 0 |
| 3 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 4 | [75%] | 93 | 93 | 89 | 89 | 0 |
| 5 | [75%] | 79 | 79 | 79 | 79 | 79 |
| 6 | [75%] | 81 | 81 | 81 | 81 | 81 |
| 7 | [75%] | 92 | 92 | 92 | 92 | 0 |
| 8 | [75%] | 93 | 93 | 85 | 85 | 0 |
| 9 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 18 | [100%] | 97 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 92 | 0 | 0 | 0 | 0 |
| 20 | [75%] | 80 | 80 | 0 | 0 | 0 |
| 21 | [75%] | 93 | 93 | 0 | 0 | 0 |
| 22 | [75%] | 93 | 93 | 79 | 0 | 0 |
| 23 | [75%] | 93 | 93 | 93 | 0 | 0 |
| 24 | [75%] | 93 | 93 | 93 | 0 | 0 |

### E.5.3 *Hourly LCA Optimization Model* for min $NO_x$ in a day in March

**Table 6-61: Supply from the energy systems in an average day in March (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 4 | 0 | 0 | 0 | 0 | 89 | 0 |
| 2 | 0 | 17 | 0 | 0 | 0 | 0 | 92 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 109 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 116 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 122 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 102 | 0 |
| 8 | 0 | 2 | 0 | 1 | 0 | 0 | 17 | 0 |
| 9 | 0 | 0 | 0 | 0 | 35 | 33 | 0 | 108 |
| 10 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 105 |
| 11 | 0 | 0 | 0 | 0 | 131 | 124 | 0 | 87 |
| 12 | 0 | 0 | 0 | 0 | 156 | 149 | 0 | 72 |
| 13 | 0 | 0 | 0 | 0 | 178 | 170 | 0 | 61 |
| 14 | 0 | 0 | 0 | 0 | 209 | 199 | 0 | 36 |
| 15 | 0 | 0 | 0 | 0 | 222 | 211 | 0 | 21 |

| Table 6-61 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 16 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 13 |
| 17 | 0 | 0 | 0 | 0 | 180 | 171 | 0 | 44 |
| 18 | 0 | 0 | 0 | 0 | 102 | 97 | 0 | 25 |
| 19 | 0 | 1 | 5 | 25 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 2 | 8 | 0 | 0 | 9 | 0 |
| 21 | 0 | 0 | 1 | 3 | 0 | 0 | 42 | 0 |
| 22 | 0 | 0 | 0 | 1 | 0 | 0 | 50 | 0 |
| 23 | 0 | 0 | 0 | 1 | 0 | 0 | 63 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 80 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [78%] | 92 | 51 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [78%] | 92 | 51 |
| 9 | [93%] | 115 | 77 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 117 | 78 |
| 12 | [93%] | 118 | 79 |
| 13 | [93%] | 118 | 79 |
| 14 | [93%] | 119 | 79 |
| 15 | [93%] | 119 | 79 |
| 16 | [93%] | 119 | 79 |
| 17 | [93%] | 118 | 79 |
| 18 | [100%] | 127 | 99 |
| 19 | [85%] | 109 | 67 |
| 20 | [62%] | 75 | 31 |
| 21 | [78%] | 92 | 51 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 75 | 31 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | [75%] | 40 | 40 | 0 |
| 2 | [75%] | 40 | 40 | 0 |
| 3 | [75%] | 34 | 34 | 34 |
| 4 | [75%] | 40 | 34 | 34 |
| 5 | [75%] | 40 | 36 | 36 |
| 6 | [75%] | 40 | 38 | 38 |
| 7 | [75%] | 35 | 35 | 35 |
| 8 | [75%] | 40 | 40 | 0 |

| Table 6-61 (continued) | | | | |
|---|---|---|---|---|
| 9 | [100%] | 48 | 48 | 0 |
| 10 | [100%] | 48 | 48 | 0 |
| 11 | [100%] | 48 | 48 | 0 |
| 12 | [100%] | 48 | 48 | 0 |
| 13 | [100%] | 48 | 48 | 0 |
| 14 | [100%] | 48 | 48 | 0 |
| 15 | [100%] | 48 | 48 | 0 |
| 16 | [100%] | 48 | 48 | 0 |
| 17 | [100%] | 48 | 48 | 0 |
| 18 | [100%] | 49 | 0 | 0 |
| 19 | [100%] | 0 | 0 | 0 |
| 20 | [100%] | 0 | 0 | 0 |
| 21 | [75%] | 36 | 0 | 0 |
| 22 | [75%] | 39 | 0 | 0 |
| 23 | [75%] | 40 | 35 | 0 |
| 24 | [75%] | 37 | 37 | 0 |
| | | **H_MT** | | |
| Hour | MT No.<br>Part Load | 1 | 2 | 3 |
| 1 | [75%] | 93 | 93 | 0 |
| 2 | [75%] | 93 | 93 | 0 |
| 3 | [75%] | 79 | 79 | 79 |
| 4 | [75%] | 93 | 80 | 80 |
| 5 | [75%] | 93 | 84 | 84 |
| 6 | [75%] | 93 | 89 | 89 |
| 7 | [75%] | 81 | 81 | 81 |
| 8 | [75%] | 93 | 93 | 0 |
| 9 | [100%] | 96 | 96 | 0 |
| 10 | [100%] | 96 | 96 | 0 |
| 11 | [100%] | 96 | 96 | 0 |
| 12 | [100%] | 96 | 96 | 0 |
| 13 | [100%] | 96 | 96 | 0 |
| 14 | [100%] | 96 | 96 | 0 |
| 15 | [100%] | 96 | 96 | 0 |
| 16 | [100%] | 96 | 96 | 0 |
| 17 | [100%] | 96 | 96 | 0 |
| 18 | [100%] | 97 | 0 | 0 |
| 19 | [100%] | 0 | 0 | 0 |
| 20 | [100%] | 0 | 0 | 0 |
| 21 | [75%] | 84 | 0 | 0 |
| 22 | [75%] | 90 | 0 | 0 |
| 23 | [75%] | 93 | 82 | 0 |
| 24 | [75%] | 86 | 86 | 0 |

### E.5.4 *Hourly LCA Optimization Model* for min $NO_x$ in a day in April

**Table 6-62: Supply from the energy systems in an average day in April (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 2 | 0 | 0 | 0 | 0 | 17 | 0 |
| 2 | 0 | 13 | 0 | 0 | 0 | 0 | 21 | 0 |
| 3 | 0 | 7 | 0 | 0 | 0 | 0 | 43 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 46 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 1 |
| 8 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 83 |
| 9 | 0 | 0 | 0 | 0 | 45 | 43 | 0 | 205 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 0 | 143 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 0 | 83 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 0 | 34 |
| 13 | 0 | 0 | 0 | 0 | 274 | 261 | 0 | 10 |
| 14 | 0 | 0 | 4 | 21 | 294 | 280 | 0 | 0 |
| 15 | 0 | 0 | 7 | 30 | 310 | 296 | 0 | 0 |
| 16 | 0 | 0 | 8 | 39 | 313 | 298 | 0 | 0 |
| 17 | 0 | 0 | 6 | 28 | 306 | 292 | 0 | 0 |
| 18 | 0 | 0 | 7 | 30 | 241 | 229 | 0 | 0 |
| 19 | 0 | 0 | 14 | 66 | 88 | 84 | 0 | 0 |
| 20 | 0 | 0 | 5 | 21 | 41 | 39 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 8 |
| 22 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 7 |
| 23 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 7 |
| 24 | 0 | 2 | 0 | 0 | 0 | 0 | 14 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [78%] | 92 | 51 |
| 3 | [93%] | 111 | 74 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [68%] | 82 | 39 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

| Table 6-62 (continued) | | | |
|---|---|---|---|
| 17 | [104%] | 130 | 109 |
| 18 | [93%] | 120 | 80 |
| 19 | [100%] | 127 | 99 |
| 20 | [78%] | 95 | 53 |
| 21 | [68%] | 82 | 39 |
| 22 | [62%] | 72 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 |
|---|---|---|---|
| 4 | [50%] | 23 | 0 |
| 5 | [75%] | 35 | 0 |
| 6 | [75%] | 39 | 0 |
| 7 | [75%] | 34 | 0 |
| 8 | [100%] | 49 | 0 |
| 9 | [100%] | 52 | 48 |
| 10 | [100%] | 53 | 48 |
| 11 | [100%] | 54 | 48 |
| 12 | [100%] | 55 | 48 |
| 13 | [100%] | 55 | 49 |
| 14 | [100%] | 55 | 53 |
| 15 | [100%] | 51 | 51 |
| 16 | [100%] | 52 | 52 |
| 17 | [100%] | 50 | 50 |
| 18 | [75%] | 36 | 36 |

**H_MT**

| Hour | MT No.<br>Part Load | 1 | 2 |
|---|---|---|---|
| 4 | [50%] | 65 | 0 |
| 5 | [75%] | 81 | 0 |
| 6 | [75%] | 90 | 0 |
| 7 | [75%] | 79 | 0 |
| 8 | [100%] | 98 | 0 |
| 9 | [100%] | 103 | 96 |
| 10 | [100%] | 105 | 96 |
| 11 | [100%] | 107 | 96 |
| 12 | [100%] | 109 | 96 |
| 13 | [100%] | 109 | 97 |
| 14 | [100%] | 109 | 106 |
| 15 | [100%] | 101 | 101 |
| 16 | [100%] | 103 | 103 |
| 17 | [100%] | 100 | 100 |
| 18 | [75%] | 83 | 83 |

## E.5.5 *Hourly LCA Optimization Model* for min $NO_x$ in a day in May

**Table 6-63: Supply from the energy systems in an average day in May (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 7 | 7 | 3 | 15 |
| 2 | 0 | 0 | 0 | 0 | 5 | 5 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 3 | 3 | 9 | 11 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 12 | 8 |
| 5 | 0 | 0 | 0 | 1 | 0 | 0 | 15 | 6 |
| 6 | 0 | 0 | 0 | 1 | 0 | 0 | 18 | 0 |
| 7 | 0 | 0 | 0 | 0 | 7 | 7 | 8 | 3 |
| 8 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 85 |
| 9 | 0 | 0 | 0 | 0 | 163 | 155 | 0 | 104 |
| 10 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 18 |
| 11 | 0 | 0 | 8 | 37 | 293 | 279 | 0 | 0 |
| 12 | 0 | 0 | 12 | 56 | 313 | 298 | 0 | 0 |
| 13 | 0 | 0 | 15 | 69 | 320 | 305 | 0 | 0 |
| 14 | 0 | 0 | 18 | 82 | 328 | 312 | 0 | 0 |
| 15 | 0 | 0 | 19 | 86 | 343 | 327 | 0 | 0 |
| 16 | 0 | 0 | 21 | 97 | 345 | 329 | 0 | 0 |
| 17 | 0 | 3 | 19 | 86 | 329 | 314 | 0 | 0 |
| 18 | 0 | 0 | 22 | 102 | 259 | 247 | 0 | 0 |
| 19 | 0 | 0 | 27 | 123 | 143 | 136 | 0 | 0 |
| 20 | 0 | 0 | 18 | 82 | 65 | 62 | 0 | 4 |
| 21 | 0 | 0 | 4 | 17 | 37 | 36 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 23 | 22 | 0 | 4 |
| 23 | 0 | 0 | 0 | 0 | 15 | 14 | 0 | 12 |
| 24 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 16 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [104%] | 130 | 109 |
| 13 | [104%] | 130 | 109 |
| 14 | [104%] | 130 | 109 |
| 15 | [93%] | 120 | 80 |
| 16 | [93%] | 113 | 75 |

Table 6-63 (continued)

| | | | |
|---|---|---|---|
| 17 | [104%] | 130 | 109 |
| 18 | [93%] | 120 | 80 |
| 19 | [85%] | 111 | 68 |
| 20 | [93%] | 111 | 74 |
| 21 | [68%] | 87 | 42 |
| 22 | [62%] | 77 | 32 |
| 23 | [62%] | 79 | 33 |
| 24 | [62%] | 76 | 31 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [75%] | 37 | 0 | 0 |
| 9 | [100%] | 50 | 48 | 0 |
| 10 | [100%] | 51 | 48 | 0 |
| 11 | [100%] | 55 | 53 | 0 |
| 12 | [100%] | 52 | 52 | 0 |
| 13 | [100%] | 55 | 51 | 0 |
| 14 | [100%] | 55 | 55 | 0 |
| 15 | [100%] ,[75%] | 52 [100%] | 34 | 34 [75%] |
| 16 | [100%] ,[75%] | 48 [100%] | 48 | 34 [75%] |
| 17 | [100%] | 55 | 55 | 0 |
| 18 | [100%], [75%] | 51 [100%] | 34 [75%] | 0 |
| 19 | [75%] | 34 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [75%] | 85 | 0 | 0 |
| 9 | [100%] | 99 | 96 | 0 |
| 10 | [100%] | 101 | 96 | 0 |
| 11 | [100%] | 109 | 105 | 0 |
| 12 | [100%] | 103 | 103 | 0 |
| 13 | [100%] | 109 | 102 | 0 |
| 14 | [100%] | 109 | 109 | 0 |
| 15 | [100%], [75%] | 104 [100%] | 79 [100%] | 79 [75%] |
| 16 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 17 | [100%] | 109 | 109 | 0 |
| 18 | [100%], [75%] | 101 [100%] | 79 [75%] | 0 |
| 19 | [75%] | 79 | 0 | 0 |

### E.5.6 *Hourly LCA Optimization Model* for min $NO_x$ in a day in June

**Table 6-64: Supply from the energy systems in an average day in June (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 2 | 7 | 19 | 19 | 0 | 6 |
| 2 | 0 | 0 | 0 | 0 | 22 | 21 | 5 | 4 |
| 3 | 0 | 0 | 0 | 0 | 19 | 18 | 9 | 7 |
| 4 | 0 | 0 | 0 | 0 | 15 | 14 | 12 | 11 |
| 5 | 0 | 0 | 0 | 0 | 11 | 11 | 16 | 13 |
| 6 | 0 | 0 | 0 | 0 | 9 | 9 | 19 | 14 |
| 7 | 0 | 0 | 7 | 30 | 14 | 14 | 0 | 11 |
| 8 | 0 | 0 | 5 | 24 | 160 | 152 | 0 | 0 |
| 9 | 0 | 0 | 7 | 31 | 272 | 259 | 0 | 0 |
| 10 | 0 | 0 | 18 | 84 | 311 | 296 | 0 | 0 |
| 11 | 0 | 0 | 27 | 125 | 345 | 329 | 0 | 0 |
| 12 | 0 | 0 | 34 | 157 | 350 | 333 | 0 | 0 |
| 13 | 0 | 0 | 36 | 164 | 353 | 337 | 0 | 0 |
| 14 | 0 | 0 | 39 | 177 | 359 | 342 | 0 | 0 |
| 15 | 0 | 0 | 40 | 185 | 363 | 346 | 0 | 0 |
| 16 | 0 | 0 | 45 | 208 | 366 | 348 | 0 | 0 |
| 17 | 0 | 0 | 43 | 199 | 364 | 347 | 0 | 0 |
| 18 | 0 | 0 | 45 | 207 | 288 | 274 | 0 | 0 |
| 19 | 0 | 0 | 51 | 232 | 179 | 170 | 0 | 0 |
| 20 | 0 | 7 | 33 | 151 | 113 | 108 | 0 | 0 |
| 21 | 0 | 0 | 15 | 71 | 53 | 51 | 0 | 0 |
| 22 | 0 | 0 | 6 | 27 | 37 | 35 | 0 | 0 |
| 23 | 0 | 0 | 2 | 9 | 36 | 34 | 0 | 0 |
| 24 | 0 | 0 | 1 | 6 | 28 | 26 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 119 | 80 |
| 13 | [93%] | 120 | 80 |

Table 6-64 (continued)

| | | | |
|---|---|---|---|
| 14 | [93%] | 120 | 80 |
| 15 | [93%] | 120 | 80 |
| 16 | [93%] | 117 | 78 |
| 17 | [93%] | 115 | 77 |
| 18 | [93%] | 120 | 80 |
| 19 | [93%] | 120 | 80 |
| 20 | [104%] | 130 | 109 |
| 21 | [78%] | 101 | 57 |
| 22 | [68%] | 85 | 41 |
| 23 | [68%] | 83 | 40 |
| 24 | [62%] | 78 | 32 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [75%] | 38 | 0 | 0 |
| 9 | [100%] | 49 | 49 | 0 |
| 10 | [100%] | 53 | 48 | 0 |
| 11 | [100%], [75%] | 53 [100%] | 34 [75%] | 34 [75%] |
| 12 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 13 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 14 | [100%], [75%] | 50 [100%] | 50 [100%] | 34 [75%] |
| 15 | [100%], [75%] | 50 [100%] | 50 [100%] | 34 [75%] |
| 16 | [100%] | 48 | 48 | 48 |
| 17 | [100%] | 48 | 48 | 48 |
| 18 | [100%] | 55 | 49 | 0 |
| 19 | [100%] | 50 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [75%] | 38 | 0 | 0 |
| 9 | [100%] | 97 | 97 | 0 |
| 10 | [100%] | 106 | 96 | 0 |
| 11 | [100%], [75%] | 105 [100%] | 34 [75%] | 34 [75%] |
| 12 | [100%], [75%] | 96 [100%] | 96 [100%] | 34 [75%] |
| 13 | [100%], [75%] | 96 [100%] | 96 [100%] | 34 [75%] |
| 14 | [100%], [75%] | 99 [100%] | 99 [100%] | 34 [75%] |
| 15 | [100%], [75%] | 101 [100%] | 101 [100%] | 34 [75%] |
| 16 | [100%] | 96 | 96 | 96 |
| 17 | [100%] | 96 | 96 | 96 |
| 18 | [100%] | 109 | 98 | 0 |
| 19 | [100%] | 100 | 0 | 0 |

### E.5.7 *Hourly LCA Optimization Model* for min $NO_x$ in a day in July

**Table 6-65: Supply from the energy systems in an average day in July (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 7 | 30 | 30 | 29 | 0 | 4 |
| 2 | 0 | 0 | 6 | 25 | 27 | 25 | 0 | 0 |
| 3 | 0 | 0 | 7 | 30 | 15 | 15 | 0 | 10 |
| 4 | 0 | 0 | 8 | 38 | 0 | 0 | 2 | 25 |
| 5 | 0 | 0 | 7 | 31 | 0 | 0 | 8 | 25 |
| 6 | 0 | 0 | 6 | 27 | 0 | 0 | 12 | 25 |
| 7 | 0 | 0 | 8 | 37 | 27 | 26 | 0 | 0 |
| 8 | 0 | 0 | 13 | 61 | 175 | 167 | 0 | 0 |
| 9 | 0 | 0 | 13 | 59 | 313 | 298 | 0 | 0 |
| 10 | 0 | 0 | 29 | 132 | 351 | 334 | 0 | 0 |
| 11 | 0 | 0 | 44 | 201 | 374 | 356 | 0 | 0 |
| 12 | 0 | 0 | 55 | 252 | 396 | 377 | 0 | 0 |
| 13 | 0 | 0 | 60 | 275 | 408 | 388 | 0 | 0 |
| 14 | 0 | 0 | 61 | 278 | 420 | 400 | 0 | 0 |
| 15 | 0 | 0 | 65 | 300 | 429 | 409 | 0 | 0 |
| 16 | 0 | 0 | 70 | 322 | 440 | 419 | 0 | 0 |
| 17 | 0 | 0 | 69 | 318 | 439 | 418 | 0 | 0 |
| 18 | 0 | 0 | 67 | 305 | 358 | 341 | 0 | 0 |
| 19 | 0 | 0 | 66 | 300 | 252 | 240 | 0 | 0 |
| 20 | 0 | 0 | 45 | 204 | 154 | 146 | 0 | 0 |
| 21 | 0 | 0 | 26 | 118 | 75 | 71 | 0 | 0 |
| 22 | 0 | 0 | 15 | 69 | 51 | 48 | 0 | 0 |
| 23 | 0 | 0 | 9 | 43 | 48 | 46 | 0 | 0 |
| 24 | 0 | 0 | 8 | 36 | 38 | 36 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [68%] | 82 | 39 |
| 2 | [62%] | 77 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 77 | 32 |
| 8 | [93%] | 120 | 80 |
| 9 | [104%] | 130 | 109 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [104%] | 130 | 109 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

| Table 6-65 (continued) | | | |
|---|---|---|---|
| 17 | [104%] | 130 | 109 |
| 18 | [93%] | 120 | 80 |
| 19 | [93%] | 120 | 80 |
| 20 | [93%] | 113 | 75 |
| 21 | [93%] | 116 | 77 |
| 22 | [78%] | 97 | 54 |
| 23 | [78%] | 92 | 52 |
| 24 | [68%] | 87 | 42 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 52 | 0 | 0 |
| 9 | [100%] | 51 | 51 | 0 |
| 10 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 11 | [100%] | 50 | 48 | 48 |
| 12 | [100%] | 55 | 51 | 51 |
| 13 | [100%] | 55 | 55 | 53 |
| 14 | [100%] | 55 | 49 | 49 |
| 15 | [100%] | 55 | 55 | 49 |
| 16 | [100%] | 55 | 55 | 55 |
| 17 | [100%] | 54 | 54 | 54 |
| 18 | [100%], [75%] | 49 [100%] | 49 [100%] | 34 [75%] |
| 19 | [75%] | 37 | 37 | 0 |
| 20 | [75%] | 34 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 103 | 0 | 0 |
| 9 | [100%] | 102 | 102 | 0 |
| 10 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 11 | [100%] | 101 | 96 | 96 |
| 12 | [100%] | 109 | 102 | 102 |
| 13 | [100%] | 109 | 109 | 105 |
| 14 | [100%] | 109 | 98 | 98 |
| 15 | [100%] | 109 | 109 | 97 |
| 16 | [100%] | 109 | 109 | 109 |
| 17 | [100%] | 108 | 108 | 108 |
| 18 | [100%], [75%] | 98 [100%] | 98 [100%] | 79 [75%] |
| 19 | [75%] | 85 | 85 | 0 |
| 20 | [75%] | 79 | 0 | 0 |

### E.5.8 *Hourly LCA Optimization Model* for min $NO_x$ in a day in August

**Table 6-66: Supply from the energy systems in an average day in August (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 5 | 21 | 28 | 26 | 0 | 0 |
| 2 | 0 | 0 | 4 | 16 | 24 | 23 | 0 | 2 |
| 3 | 0 | 0 | 7 | 34 | 0 | 0 | 0 | 25 |
| 4 | 0 | 0 | 6 | 29 | 0 | 0 | 4 | 25 |
| 5 | 0 | 0 | 5 | 25 | 0 | 0 | 9 | 25 |
| 6 | 0 | 0 | 5 | 22 | 0 | 0 | 13 | 25 |
| 7 | 0 | 0 | 7 | 30 | 4 | 3 | 0 | 21 |
| 8 | 0 | 0 | 6 | 26 | 164 | 156 | 0 | 0 |
| 9 | 0 | 0 | 10 | 46 | 297 | 283 | 0 | 0 |
| 10 | 0 | 0 | 24 | 111 | 349 | 332 | 0 | 0 |
| 11 | 0 | 0 | 43 | 196 | 371 | 354 | 0 | 0 |
| 12 | 0 | 0 | 51 | 235 | 391 | 372 | 0 | 0 |
| 13 | 0 | 0 | 55 | 252 | 399 | 380 | 0 | 0 |
| 14 | 0 | 0 | 59 | 269 | 405 | 386 | 0 | 0 |
| 15 | 0 | 0 | 61 | 280 | 422 | 402 | 0 | 0 |
| 16 | 0 | 0 | 65 | 298 | 430 | 409 | 0 | 0 |
| 17 | 0 | 0 | 62 | 284 | 423 | 403 | 0 | 0 |
| 18 | 0 | 0 | 54 | 247 | 342 | 325 | 0 | 0 |
| 19 | 0 | 0 | 54 | 248 | 204 | 194 | 0 | 0 |
| 20 | 0 | 0 | 32 | 148 | 106 | 101 | 0 | 0 |
| 21 | 0 | 0 | 16 | 72 | 60 | 57 | 0 | 0 |
| 22 | 0 | 0 | 10 | 45 | 39 | 37 | 0 | 0 |
| 23 | 0 | 0 | 6 | 27 | 38 | 36 | 0 | 0 |
| 24 | 0 | 0 | 4 | 20 | 35 | 34 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 79 | 32 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 116 | 77 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

| Table 6-66 (continued) | | | |
|---|---|---|---|
| 17 | [104%] | 130 | 109 |
| 18 | [93%] | 120 | 80 |
| 19 | [104%] | 130 | 109 |
| 20 | [104%] | 129 | 109 |
| 21 | [85%] | 103 | 63 |
| 22 | [68%] | 90 | 43 |
| 23 | [68%] | 88 | 42 |
| 24 | [68%] | 82 | 40 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 48 | 0 | 0 |
| 9 | [100%] | 55 | 55 | 0 |
| 10 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 11 | [100%] | 49 | 48 | 48 |
| 12 | [100%] | 55 | 52 | 48 |
| 13 | [100%] | 55 | 52 | 52 |
| 14 | [100%] | 55 | 53 | 53 |
| 15 | [100%] | 52 | 52 | 52 |
| 16 | [100%] | 55 | 52 | 52 |
| 17 | [100%] | 52 | 52 | 52 |
| 18 | [100%], [75%] | 50 [100%] | 34 [75%] | 34 [75%] |
| 19 | [100%] | 48 | 0 | 0 |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 8 | [100%] | 96 | 0 | 0 |
| 9 | [100%] | 109 | 109 | 0 |
| 10 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 11 | [100%] | 98 | 96 | 96 |
| 12 | [100%] | 109 | 104 | 96 |
| 13 | [100%] | 109 | 103 | 103 |
| 14 | [100%] | 109 | 106 | 106 |
| 15 | [100%] | 103 | 103 | 103 |
| 16 | [100%] | 109 | 104 | 104 |
| 17 | [100%] | 104 | 104 | 104 |
| 18 | [100%], [75%] | 101 [100%] | 79 [75%] | 79 [75%] |
| 19 | [100%] | 96 | 0 | 0 |

### E.5.9 *Hourly LCA Optimization Model* for min $NO_x$ in a day in September

**Table 6-67: Supply from the energy systems in an average day in September (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 16 | 15 | 2 | 10 |
| 2 | 0 | 0 | 0 | 0 | 12 | 12 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 10 | 9 | 9 | 15 |
| 4 | 0 | 0 | 0 | 0 | 7 | 7 | 12 | 15 |
| 5 | 0 | 0 | 0 | 0 | 6 | 5 | 16 | 13 |
| 6 | 0 | 0 | 0 | 0 | 4 | 4 | 19 | 11 |
| 7 | 0 | 0 | 0 | 0 | 8 | 7 | 9 | 5 |
| 8 | 0 | 0 | 0 | 0 | 79 | 75 | 0 | 64 |
| 9 | 0 | 0 | 0 | 0 | 173 | 165 | 0 | 88 |
| 10 | 0 | 0 | 3 | 15 | 269 | 256 | 0 | 0 |
| 11 | 0 | 0 | 16 | 72 | 308 | 293 | 0 | 0 |
| 12 | 0 | 0 | 23 | 107 | 323 | 308 | 0 | 0 |
| 13 | 0 | 0 | 26 | 120 | 348 | 331 | 0 | 0 |
| 14 | 0 | 0 | 31 | 143 | 350 | 334 | 0 | 0 |
| 15 | 0 | 0 | 36 | 166 | 357 | 340 | 0 | 0 |
| 16 | 0 | 0 | 39 | 180 | 361 | 344 | 0 | 0 |
| 17 | 0 | 0 | 34 | 154 | 350 | 333 | 0 | 0 |
| 18 | 0 | 0 | 28 | 128 | 261 | 249 | 0 | 0 |
| 19 | 0 | 0 | 25 | 116 | 141 | 134 | 0 | 0 |
| 20 | 0 | 0 | 14 | 63 | 58 | 56 | 0 | 0 |
| 21 | 0 | 0 | 6 | 26 | 39 | 37 | 0 | 0 |
| 22 | 0 | 0 | 2 | 8 | 28 | 26 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 25 | 24 | 0 | 3 |
| 24 | 0 | 0 | 0 | 0 | 20 | 19 | 0 | 6 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 118 | 79 |
| 9 | [93%] | 114 | 76 |
| 10 | [93%] | 120 | 80 |
| 11 | [104%] | 130 | 109 |
| 12 | [104%] | 130 | 109 |
| 13 | [93%] | 120 | 80 |

Table 6-67 (continued)

| | | | |
|---|---|---|---|
| 14 | [93%] | 117 | 78 |
| 15 | [93%] | 120 | 80 |
| 16 | [93%] | 120 | 80 |
| 17 | [93%] | 120 | 80 |
| 18 | [93%] | 120 | 80 |
| 19 | [85%] | 105 | 65 |
| 20 | [85%] | 104 | 64 |
| 21 | [68%] | 89 | 43 |
| 22 | [62%] | 79 | 32 |
| 23 | [62%] | 80 | 33 |
| 24 | [62%] | 76 | 31 |

**P_MT**

| Hour | MT No. | 1 | 2 | 3 |
|---|---|---|---|---|
| | Part Load | | | |
| 8 | [75%] | 34 | 0 | 0 |
| 9 | [100%] | 48 | 48 | 0 |
| 10 | [100%] | 48 | 48 | 0 |
| 11 | [100%] | 50 | 50 | 0 |
| 12 | [100%] | 55 | 53 | 0 |
| 13 | [100%], [75%] | 54 100%] | 34 [75%] | 34 [75%] |
| 14 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 15 | [100%], [75%] | 50 [100%] | 48 [100%] | 34 [75%] |
| 16 | [100%], [75%] | 50 [100%] | 50 [100%] | 34 [75%] |
| 17 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] |
| 18 | [100%], [75%] | 51 100%] | 34 [75%] | 0 |
| 19 | [75%] | 34 | 0 | 0 |

**H_MT**

| Hour | MT No. | 1 | 2 | 3 |
|---|---|---|---|---|
| | Part Load | | | |
| 8 | [75%] | 79 | 0 | 0 |
| 9 | [100%] | 96 | 96 | 0 |
| 10 | [100%] | 96 | 96 | 0 |
| 11 | [100%] | 99 | 99 | 0 |
| 12 | [100%] | 109 | 106 | 0 |
| 13 | [100%], [75%] | 107 100%] | 79 [75%] | 79 [75%] |
| 14 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 15 | [100%], [75%] | 99 [100%] | 96 [100%] | 79 [75%] |
| 16 | [100%], [75%] | 101 [100%] | 101 [100%] | 79 [75%] |
| 17 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] |
| 18 | [100%], [75%] | 103 100%] | 79 [75%] | 0 |
| 19 | [75%] | 79 | 0 | 0 |

## E.5.10 *Hourly LCA Optimization Model* for min $NO_x$ in a day in October

**Table 6-68: Supply from the energy systems in an average day in October (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 4 | 0 | 0 | 0 | 0 | 17 | 0 |
| 2 | 0 | 17 | 0 | 0 | 0 | 0 | 20 | 0 |
| 3 | 0 | 9 | 0 | 0 | 0 | 0 | 43 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 46 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 54 | 0 |
| 7 | 0 | 1 | 0 | 0 | 0 | 0 | 43 | 0 |
| 8 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 50 |
| 9 | 0 | 0 | 0 | 0 | 24 | 23 | 0 | 218 |
| 10 | 0 | 0 | 0 | 0 | 107 | 102 | 0 | 153 |
| 11 | 0 | 0 | 0 | 0 | 208 | 198 | 0 | 58 |
| 12 | 0 | 0 | 1 | 5 | 275 | 262 | 0 | 0 |
| 13 | 0 | 0 | 7 | 32 | 289 | 275 | 0 | 0 |
| 14 | 0 | 0 | 10 | 45 | 307 | 292 | 0 | 0 |
| 15 | 0 | 0 | 13 | 60 | 316 | 301 | 0 | 0 |
| 16 | 0 | 0 | 13 | 60 | 312 | 298 | 0 | 0 |
| 17 | 0 | 0 | 8 | 35 | 289 | 275 | 0 | 0 |
| 18 | 0 | 0 | 3 | 12 | 212 | 202 | 0 | 0 |
| 19 | 0 | 0 | 2 | 11 | 59 | 56 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 17 |
| 21 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 22 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 16 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 24 | 0 | 5 | 0 | 0 | 0 | 0 | 4 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [78%] | 92 | 51 |
| 3 | [93%] | 111 | 74 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [93%] | 119 | 79 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [104%] | 130 | 109 |
| 15 | [104%] | 130 | 109 |
| 16 | [104%] | 130 | 109 |

Table 6-68 (continued)

| | | | |
|---|---|---|---|
| 17 | [93%] | 120 | 80 |
| 18 | [104%] | 130 | 109 |
| 19 | [85%] | 109 | 67 |
| 20 | [68%] | 85 | 41 |
| 21 | [62%] | 80 | 33 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [68%] | 82 | 39 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 |
|---|---|---|---|
| 4 | [50%] | 23 | 0 |
| 5 | [75%] | 34 | 0 |
| 6 | [75%] | 40 | 0 |
| 7 | [75%] | 40 | 0 |
| 8 | [75%] | 36 | 0 |
| 9 | [100%] | 48 | 48 |
| 10 | [100%] | 48 | 48 |
| 11 | [100%] | 49 | 48 |
| 12 | [100%] | 52 | 48 |
| 13 | [100%] | 55 | 51 |
| 14 | [100%] | 50 | 50 |
| 15 | [100%] | 55 | 49 |
| 16 | [100%] | 52 | 52 |
| 17 | [100%] | 55 | 51 |
| 18 | [100%] | 54 | 0 |

**H_MT**

| Hour | MT No.<br>Part Load | 1 | 2 |
|---|---|---|---|
| 4 | [50%] | 65 | 0 |
| 5 | [75%] | 79 | 0 |
| 6 | [75%] | 92 | 0 |
| 7 | [75%] | 93 | 0 |
| 8 | [75%] | 83 | 0 |
| 9 | [100%] | 96 | 96 |
| 10 | [100%] | 96 | 96 |
| 11 | [100%] | 97 | 96 |
| 12 | [100%] | 103 | 96 |
| 13 | [100%] | 109 | 101 |
| 14 | [100%] | 99 | 99 |
| 15 | [100%] | 109 | 98 |
| 16 | [100%] | 103 | 103 |
| 17 | [100%] | 109 | 102 |
| 18 | [100%] | 107 | 0 |

## E.5.11 *Hourly LCA Optimization Model* for min $NO_x$ in a day in November

**Table 6-69: Supply from the energy systems in an average day in November (Hourly model: min NOx).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 88 | 0 |
| 2 | 0 | 4 | 0 | 0 | 0 | 0 | 92 | 0 |
| 3 | 0 | 12 | 0 | 0 | 0 | 0 | 95 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 94 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 107 | 4 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 111 | 0 |
| 7 | 0 | 17 | 0 | 0 | 0 | 0 | 95 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 |
| 9 | 0 | 0 | 0 | 0 | 12 | 11 | 0 | 137 |
| 10 | 0 | 0 | 0 | 0 | 40 | 38 | 0 | 163 |
| 11 | 0 | 0 | 0 | 0 | 67 | 63 | 0 | 159 |
| 12 | 0 | 0 | 0 | 0 | 106 | 101 | 0 | 128 |
| 13 | 0 | 0 | 0 | 0 | 137 | 131 | 0 | 100 |
| 14 | 0 | 0 | 0 | 0 | 157 | 149 | 0 | 86 |
| 15 | 0 | 0 | 0 | 0 | 168 | 160 | 0 | 66 |
| 16 | 0 | 0 | 0 | 0 | 141 | 134 | 0 | 78 |
| 17 | 0 | 0 | 0 | 0 | 76 | 73 | 0 | 120 |
| 18 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 78 |
| 19 | 0 | 8 | 0 | 2 | 0 | 0 | 11 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 0 |
| 21 | 0 | 15 | 0 | 0 | 0 | 0 | 46 | 0 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 63 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 77 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 86 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [78%] | 92 | 51 |
| 2 | [78%] | 92 | 51 |
| 3 | [78%] | 92 | 51 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [78%] | 92 | 51 |
| 8 | [68%] | 82 | 39 |
| 9 | [93%] | 120 | 80 |
| 10 | [93%] | 120 | 80 |
| 11 | [93%] | 120 | 80 |
| 12 | [93%] | 120 | 80 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [93%] | 120 | 80 |
| 16 | [93%] | 120 | 80 |

| Table 6-69 (continued) | | | |
|---|---|---|---|
| 17 | [93%] | 120 | 80 |
| 18 | [93%] | 120 | 80 |
| 19 | [93%] | 111 | 74 |
| 20 | [62%] | 75 | 31 |
| 21 | [78%] | 92 | 51 |
| 22 | [62%] | 75 | 31 |
| 23 | [78%] | 92 | 51 |
| 24 | [78%] | 92 | 51 |

**P_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | [75%] | 39 | 39 | 0 |
| 2 | [75%] | 40 | 40 | 0 |
| 3 | [75%] | 40 | 40 | 0 |
| 4 | [75%] | 36 | 36 | 0 |
| 5 | [75%] | 34 | 34 | 34 |
| 6 | [75%] | 35 | 34 | 34 |
| 7 | [75%] | 40 | 40 | 0 |
| 8 | [75%] | 39 | 39 | 0 |
| 9 | [100%], [75%] | 50 [100%] | 34 [75%] | 0 |
| 10 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 11 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 12 | [100%], [75%] | 50 [100%] | 34 [75%] | 0 |
| 13 | [100%], [75%] | 50 [100%] | 34 [75%] | 0 |
| 14 | [100%], [75%] | 51 [100%] | 34 [75%] | 0 |
| 15 | [100%], [75%] | 51 [100%] | 34 [75%] | 0 |
| 16 | [100%], [75%] | 50 [100%] | 34 [75%] | 0 |
| 17 | [100%], [75%] | 49 [100%] | 34 [75%] | 0 |
| 18 | [100%] | 48 | 0 | 0 |
| 19 | | | | |
| 20 | [75%] | 38 | 0 | |
| 21 | [75%] | 40 | 0 | |
| 22 | [75%] | 36 | 36 | |
| 23 | [75%] | 37 | 37 | |
| 24 | [75%] | 40 | 40 | |

**H_MT**

| Hour | MT No. / Part Load | 1 | 2 | 3 |
|---|---|---|---|---|
| 1 | [75%] | 91 | 91 | 0 |
| 2 | [75%] | 93 | 93 | 0 |
| 3 | [75%] | 93 | 93 | 0 |
| 4 | [75%] | 84 | 84 | 0 |
| 5 | [75%] | 79 | 79 | 79 |
| 6 | [75%] | 82 | 79 | 79 |
| 7 | [75%] | 93 | 93 | 0 |
| 8 | [75%] | 91 | 91 | 0 |
| 9 | [100%], [75%] | 99 [100%] | 79 [75%] | 0 |

| Table 6-69 (continued) | | | | |
|---|---|---|---|---|
| 10 | [100%], [75%] | 97 [100%] | 79 [75%] | 0 |
| 11 | [100%], [75%] | 97 [100%] | 79 [75%] | 0 |
| 12 | [100%], [75%] | 99 [100%] | 79 [75%] | 0 |
| 13 | [100%], [75%] | 99 [100%] | 79 [75%] | 0 |
| 14 | [100%], [75%] | 101 [100%] | 79 [75%] | 0 |
| 15 | [100%], [75%] | 101 [100%] | 79 [75%] | 0 |
| 16 | [100%], [75%] | 99 [100%] | 79 [75%] | 0 |
| 17 | [100%], [75%] | 97 [100%] | 79 [75%] | 0 |
| 18 | [100%] | 48 | 0 | 0 |
| 20 | [75%] | 88 | 0 | |
| 21 | [75%] | 93 | 0 | |
| 22 | [75%] | 83 | 83 | |
| 23 | [75%] | 85 | 85 | |
| 24 | [75%] | 93 | 93 | |

### E.5.12 *Hourly LCA Optimization Model* for min $NO_x$ in a day in December

**Table 6-70: Supply from the energy systems in an average day in December (Hourly model: min $NO_x$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 136 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 143 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 150 | 0 |
| 4 | 0 | 3 | 0 | 0 | 0 | 0 | 154 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 169 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 175 | 0 |
| 7 | 0 | 6 | 0 | 0 | 0 | 0 | 150 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 88 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| 10 | 0 | 0 | 0 | 0 | 5 | 4 | 0 | 78 |
| 11 | 0 | 0 | 0 | 0 | 15 | 15 | 0 | 125 |
| 12 | 0 | 0 | 0 | 0 | 29 | 28 | 0 | 141 |
| 13 | 0 | 0 | 0 | 0 | 57 | 55 | 0 | 124 |
| 14 | 0 | 0 | 0 | 0 | 78 | 75 | 0 | 113 |
| 15 | 0 | 0 | 0 | 0 | 81 | 77 | 0 | 113 |
| 16 | 0 | 0 | 0 | 0 | 52 | 49 | 0 | 126 |
| 17 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 112 |
| 18 | 0 | 0 | 1 | 3 | 3 | 3 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 38 | 0 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 76 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 101 | 0 |
| 22 | 0 | 8 | 0 | 0 | 0 | 0 | 121 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 119 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 127 | 0 |

Table 6-70 (continued)

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [78%] | 92 | 51 |
| 6 | [78%] | 92 | 51 |
| 7 | [62%] | 75 | 31 |
| 8 | [62%] | 75 | 31 |
| 9 | [104%] | 130 | 109 |
| 10 | [93%] | 116 | 77 |
| 11 | [93%] | 115 | 77 |
| 12 | [93%] | 115 | 77 |
| 13 | [93%] | 115 | 77 |
| 14 | [93%] | 116 | 77 |
| 15 | [93%] | 117 | 78 |
| 16 | [93%] | 116 | 77 |
| 17 | [93%] | 115 | 77 |
| 18 | [104%] | 128 | 107 |
| 19 | [62%] | 75 | 31 |
| 20 | [62%] | 75 | 31 |
| 21 | [62%] | 75 | 31 |
| 22 | [78%] | 92 | 51 |
| 23 | [62%] | 75 | 31 |
| 24 | [62%] | 75 | 31 |

**P_MT**

| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 40 | 37 | 37 | 37 | 0 |
| 2 | [75%] | 40 | 38 | 38 | 38 | 0 |
| 3 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 4 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 5 | [75%] | 39 | 39 | 39 | 39 | 0 |
| 6 | [75%] | 39 | 39 | 39 | 39 | 0 |
| 7 | [75%] | 40 | 40 | 40 | 40 | 0 |
| 8 | [75%] | 34 | 34 | 34 | 34 | 34 |
| 9 | [100%], [75%] | 98 [100%] | 34 [75%] | 0 | 0 | 0 |
| 10 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 11 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 12 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 13 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 14 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 15 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 16 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 17 | [100%] | 48 | 48 | 0 | 0 | 0 |
| 18 | [100%] | 48 | 0 | 0 | 0 | 0 |

| Table 6-70 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 19 | [75%] | 38 | 34 | 0 | 0 | 0 |
| 20 | [75%], [50%] | 40 [75%] | 35 [75%] | 21 [50%] | 0 | 0 |
| 21 | [75%] | 39 | 39 | 39 | 0 | 0 |
| 22 | [75%] | 40 | 40 | 40 | 0 | 0 |
| 23 | [75%] | 37 | 34 | 34 | 34 | 0 |
| 24 | [75%] | 36 | 36 | 36 | 36 | 0 |
| | | | **H_MT** | | | |
| Hour | MT No.<br>Part Load | 1 | 2 | 3 | 4 | 5 |
| 1 | [75%] | 93 | 86 | 86 | 86 | 0 |
| 2 | [75%] | 93 | 89 | 89 | 89 | 0 |
| 3 | [75%] | 92 | 92 | 92 | 92 | 0 |
| 4 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 5 | [75%] | 90 | 90 | 90 | 90 | 0 |
| 6 | [75%] | 92 | 92 | 92 | 92 | 0 |
| 7 | [75%] | 93 | 93 | 93 | 93 | 0 |
| 8 | [75%] | 80 | 80 | 80 | 80 | 80 |
| 9 | [100%], [75%] | 49 [100%] | 79 [75%] | 0 | 0 | 0 |
| 10 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 11 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 12 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 13 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 14 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 15 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 16 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 17 | [100%] | 96 | 96 | 0 | 0 | 0 |
| 18 | [100%] | 96 | 0 | 0 | 0 | 0 |
| 19 | [75%] | 88 | 79 | 0 | 0 | 0 |
| 20 | [75%], [50%] | 93 [75%] | 81 [75%] | 58 [50%] | 0 | 0 |
| 21 | [75%] | 92 | 92 | 92 | 0 | 0 |
| 22 | [75%] | 93 | 93 | 93 | 0 | 0 |
| 23 | [75%] | 86 | 79 | 79 | 79 | 0 |
| 24 | [75%] | 83 | 83 | 83 | 83 | 0 |

# E.6 AVERAGE ELECTRIC OPTION: MIN $SO_2$

## E.6.1 *Hourly LCA Optimization Model* for min $SO_2$ in a day in January

**Table 6-71: Supply from the energy systems in an average day in January (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 242 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 259 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 273 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 289 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 306 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 321 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 286 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 145 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 33 |
| 10 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 146 |
| 11 | 0 | 0 | 0 | 0 | 9 | 8 | 0 | 212 |
| 12 | 0 | 0 | 0 | 0 | 22 | 21 | 0 | 229 |
| 13 | 0 | 0 | 0 | 0 | 35 | 34 | 0 | 235 |
| 14 | 0 | 0 | 0 | 0 | 54 | 51 | 0 | 230 |
| 15 | 0 | 0 | 0 | 0 | 70 | 67 | 0 | 207 |
| 16 | 0 | 0 | 0 | 0 | 63 | 60 | 0 | 189 |
| 17 | 0 | 0 | 0 | 0 | 28 | 27 | 0 | 172 |
| 18 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 54 |
| 19 | 0 | 52 | 0 | 0 | 0 | 0 | 3 | 0 |
| 20 | 0 | 110 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 187 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 231 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |
| 15 | [100%] | 48 | 96 |
| 16 | [100%] | 48 | 96 |

| Table 6-71 (continued) | | | |
|---|---|---|---|
| 17 | [100%] | 48 | 96 |
| 18 | [25%] | 9 | 40 |
| 23 | [25%] | 9 | 40 |

| Hour | MT No.<br>Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 92 | 210 |
| 2 | [50%] | 89 | 203 |
| 3 | [50%] | 87 | 199 |
| 4 | [50%] | 84 | 192 |
| 5 | [50%] | 81 | 185 |
| 6 | [50%] | 78 | 178 |
| 7 | [50%] | 88 | 201 |
| 8 | [50%] | 84 (unit 1)<br>76 (unit 2) | 192 (unit 1)<br>174 (unit 2) |
| 9 | [100%] | 166 | 273 |
| 10 | [100%] | 164 | 269 |
| 11 | [100%] | 163 | 268 |
| 12 | [100%] | 163 | 268 |
| 13 | [100%] | 163 | 268 |
| 14 | [100%] | 163 | 268 |
| 15 | [100%] | 163 | 268 |
| 16 | [100%] | 164 | 269 |
| 17 | [100%] | 164 | 269 |
| 18 | [100%] | 168 | 276 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 97 | 221 |
| 21 | [50%] | 95 | 217 |
| 22 | [50%] | 93 | 212 |
| 23 | [50%] | 89 | 203 |
| 24 | [50%] | 95 | 217 |

### E.6.2 *Hourly LCA Optimization Model* for min $SO_2$ in a day in February

**Table 6-72: Supply from the energy systems in an average day in February (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 177 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 214 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 232 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 248 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 263 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 229 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 133 |

Table 6-72 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | 0 | 0 | 0 | 0 | 21 | 20 | 0 | 210 |
| 11 | 0 | 0 | 0 | 0 | 41 | 39 | 0 | 232 |
| 12 | 0 | 0 | 0 | 0 | 64 | 61 | 0 | 236 |
| 13 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 234 |
| 14 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 226 |
| 15 | 0 | 0 | 0 | 0 | 121 | 116 | 0 | 197 |
| 16 | 0 | 0 | 0 | 0 | 120 | 114 | 0 | 184 |
| 17 | 0 | 0 | 0 | 0 | 97 | 92 | 0 | 191 |
| 18 | 0 | 0 | 0 | 0 | 27 | 26 | 0 | 161 |
| 19 | 0 | 0 | 0 | 0 | 1 | 1 | 8 | 71 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 |
| 21 | 0 | 39 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 118 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 127 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |
| 15 | [100%] | 48 | 96 |
| 16 | [100%] | 48 | 96 |
| 17 | [100%] | 48 | 96 |
| 18 | [25%] | 9 | 40 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 78 | 178 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 81 (unit 1)<br>76 (unit 2) | 185 (unit 1)<br>174 (unit 2) |
| 9 | [100%] | 164 | 269 |
| 10 | [100%] | 164 | 269 |
| 11 | [100%] | 164 | 269 |
| 12 | [100%] | 164 | 269 |
| 13 | [100%] | 164 | 269 |
| 14 | [100%] | 164 | 269 |
| 15 | [100%] | 164 | 269 |
| 16 | [100%] | 164 | 269 |
| 17 | [100%] | 164 | 269 |

| Table 6-72 (continued) | | | |
|---|---|---|---|
| 18 | [100%] | 167 | 274 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 91 | 208 |
| 21 | [50%] | 89 | 203 |
| 22 | [50%] | 88 | 201 |
| 23 | [50%] | 93 | 212 |
| 24 | [50%] | 91 | 208 |

## E.6.3 Hourly LCA Optimization Model for min $SO_2$ in a day in March

**Table 6-73: Supply from the energy systems in an average day in March (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 54 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 74 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 92 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 109 | 0 | 0 | 0 | 0 | 2 | 0 |
| 5 | 0 | 118 | 0 | 0 | 0 | 0 | 5 | 0 |
| 6 | 0 | 127 | 0 | 0 | 0 | 0 | 8 | 0 |
| 7 | 0 | 99 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 13 |
| 9 | 0 | 0 | 0 | 0 | 35 | 33 | 0 | 204 |
| 10 | 0 | 0 | 0 | 0 | 86 | 82 | 0 | 202 |
| 11 | 0 | 0 | 0 | 0 | 131 | 124 | 0 | 184 |
| 12 | 0 | 0 | 0 | 0 | 156 | 149 | 0 | 170 |
| 13 | 0 | 0 | 0 | 0 | 178 | 170 | 0 | 159 |
| 14 | 0 | 0 | 0 | 0 | 209 | 199 | 0 | 135 |
| 15 | 0 | 0 | 0 | 0 | 222 | 211 | 0 | 120 |
| 16 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 112 |
| 17 | 0 | 0 | 0 | 0 | 180 | 171 | 0 | 142 |
| 18 | 0 | 0 | 0 | 0 | 102 | 97 | 0 | 144 |
| 19 | 0 | 0 | 0 | 0 | 25 | 24 | 9 | 123 |
| 20 | 0 | 0 | 0 | 0 | 8 | 7 | 0 | 94 |
| 21 | 0 | 0 | 0 | 0 | 3 | 3 | 0 | 56 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 9 |
| 23 | 0 | 7 | 0 | 1 | 0 | 0 | 0 | 0 |
| 24 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |

| Table 6-73 (continued) | | | |
|---|---|---|---|
| 15 | [100%] | 48 | 96 |
| 16 | [100%] | 48 | 96 |
| 17 | [100%] | 48 | 96 |
| 18 | [25%] | 9 | 40 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 77 | 176 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 77 | 176 |
| 8 | [100%] | 154 | 253 |
| 9 | [100%] | 163 | 268 |
| 10 | [100%] | 164 | 269 |
| 11 | [100%] | 165 | 271 |
| 12 | [100%] | 166 | 273 |
| 13 | [100%] | 166 | 273 |
| 14 | [100%] | 167 | 274 |
| 15 | [100%] | 167 | 274 |
| 16 | [100%] | 167 | 274 |
| 17 | [100%] | 166 | 273 |
| 18 | [100%] | 167 | 274 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 87 | 199 |
| 21 | [50%] | 85 | 194 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 87 | 199 |
| 24 | [50%] | 85 | 194 |

### E.6.4 *Hourly LCA Optimization Model* for min $SO_2$ in a day in April

**Table 6-74: Supply from the energy systems in an average day in April (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 121 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 110 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 93 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 78 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 62 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 45 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 65 |
| 8 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 180 |

Table 6-74 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 9 | 0 | 0 | 0 | 0 | 45 | 43 | 0 | 304 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 0 | 242 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 5 | 222 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 4 | 170 |
| 13 | 0 | 0 | 3 | 14 | 260 | 248 | 0 | 158 |
| 14 | 0 | 0 | 0 | 0 | 314 | 299 | 3 | 106 |
| 15 | 0 | 0 | 0 | 0 | 341 | 325 | 2 | 81 |
| 16 | 0 | 0 | 2 | 9 | 343 | 326 | 0 | 78 |
| 17 | 0 | 0 | 0 | 0 | 334 | 318 | 3 | 86 |
| 18 | 0 | 0 | 0 | 0 | 271 | 258 | 0 | 53 |
| 19 | 0 | 0 | 0 | 0 | 153 | 146 | 0 | 54 |
| 20 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 133 |
| 21 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 156 |
| 22 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 149 |
| 23 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 155 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 123 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 49 | 98 |
| 18 | [50%] | 21 | 58 |

**P_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 3 | [50%] | 76 | 0 |
| 4 | [50%] | 76 | 0 |
| 5 | [50%] | 76 | 0 |
| 6 | [50%] | 76 | 0 |
| 7 | [50%] | 76 | 0 |
| 8 | [100%] | 160 | 0 |
| 9 | [100%] | 172 | 0 |
| 10 | [100%] | 172 | 0 |
| 11 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 12 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 13 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 14 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 15 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 16 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 17 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 18 | [100%] | 164 | 0 |
| 19 | [75%] | 113 | 0 |
| 20 | [50%] | 90 | 0 |
| 21 | [50%] | 82 | 0 |
| 22 | [50%] | 76 | 0 |
| 23 | [50%] | 79 | 0 |

| Table 6-74 (continued) | | | |
|---|---|---|---|
| 24 | [50%] | 77 | 0 |
| | | **H_ICE** | |
| Hour | MT No. | 1 | 2 |
| | Part Load | | |
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 3 | [50%] | 174 | 0 |
| 4 | [50%] | 174 | 0 |
| 5 | [50%] | 174 | 0 |
| 6 | [50%] | 174 | 0 |
| 7 | [50%] | 174 | 0 |
| 8 | [100%] | 263 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 282 | 0 |
| 11 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 12 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 13 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 14 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 15 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 16 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 17 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 18 | [100%] | 270 | 0 |
| 19 | [75%] | 215 | 0 |
| 20 | [50%] | 205 | 0 |
| 21 | [50%] | 187 | 0 |
| 22 | [50%] | 174 | 0 |
| 23 | [50%] | 180 | 0 |
| 24 | [50%] | 176 | 0 |

### E.6.5 *Hourly LCA Optimization Model* for min $SO_2$ in a day in May

**Table 6-75: Supply from the energy systems in an average day in May (Hourly model: min $SO_2$).**

| **Hour** | **P_GRID** | **H_BOILER** | **P_EC** | **C_EC** | **C_AC** | **H_AC** | **P_EXCESS** | **H_EXCESS** |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 7 | 7 | 4 | 157 |
| 2 | 0 | 0 | 0 | 0 | 5 | 5 | 7 | 156 |
| 3 | 0 | 0 | 0 | 0 | 3 | 3 | 10 | 154 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 13 | 151 |
| 5 | 0 | 0 | 0 | 0 | 1 | 1 | 17 | 147 |
| 6 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 109 |
| 7 | 0 | 0 | 0 | 0 | 7 | 7 | 9 | 146 |
| 8 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 177 |
| 9 | 0 | 0 | 0 | 0 | 163 | 155 | 0 | 204 |
| 10 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 118 |
| 11 | 0 | 0 | 0 | 0 | 329 | 314 | 0 | 48 |

Table 6-75 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 12 | 0 | 0 | 0 | 0 | 369 | 352 | 0 | 11 |
| 13 | 0 | 0 | 0 | 0 | 389 | 370 | 6 | 35 |
| 14 | 0 | 0 | 5 | 23 | 387 | 368 | 0 | 37 |
| 15 | 0 | 0 | 5 | 23 | 407 | 387 | 0 | 18 |
| 16 | 0 | 0 | 5 | 23 | 420 | 400 | 0 | 5 |
| 17 | 0 | 0 | 6 | 27 | 388 | 370 | 0 | 35 |
| 18 | 0 | 0 | 5 | 25 | 336 | 320 | 0 | 0 |
| 19 | 0 | 0 | 6 | 29 | 237 | 226 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 147 | 140 | 0 | 64 |
| 21 | 0 | 0 | 0 | 0 | 55 | 52 | 0 | 132 |
| 22 | 0 | 0 | 0 | 0 | 23 | 22 | 0 | 148 |
| 23 | 0 | 0 | 0 | 0 | 15 | 14 | 0 | 160 |
| 24 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 158 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 6 | [75%], [50%] | 35 [75%] (unit 1)<br>21 [50%] (unit 2) | 83 [75%] (unit 1)<br>58 [50%] (unit 2) |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 49 | 98 |
| 18 | [50%] | 21 | 58 |

**P_ICE**

| Hour | MT No.<br>Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 3 | [50%] | 76 | 0 |
| 4 | [50%] | 76 | 0 |
| 5 | [50%] | 76 | 0 |
| 7 | [50%] | 76 | 0 |
| 8 | [100%] | 157 | 0 |
| 9 | [100%] | 170 | 0 |
| 10 | [100%] | 171 | 0 |
| 11 | [100%] | 172 | 0 |
| 12 | [100%] | 172 | 0 |
| 13 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 14 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 15 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 16 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 17 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 18 | [100%] | 168 | 0 |
| 19 | [75%] | 124 | 0 |
| 20 | [50%] | 93 | 0 |
| 21 | [50%] | 83 | 0 |
| 22 | [50%] | 77 | 0 |
| 23 | [50%] | 79 | 0 |

| Table 6-75 (continued) | | | |
|---|---|---|---|
| 24 | [50%] | 76 | 0 |
| | | **H_ICE** | |
| Hour | MT No. | 1 | 2 |
| | Part Load | | |
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 3 | [50%] | 174 | 0 |
| 4 | [50%] | 174 | 0 |
| 5 | [50%] | 174 | 0 |
| 7 | [50%] | 174 | 0 |
| 8 | [100%] | 258 | 0 |
| 9 | [100%] | 279 | 0 |
| 10 | [100%] | 281 | 0 |
| 11 | [100%] | 282 | 0 |
| 12 | [100%] | 282 | 0 |
| 13 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 14 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 15 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 16 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 17 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 18 | [100%] | 276 | 0 |
| 19 | [75%] | 237 | 0 |
| 20 | [50%] | 212 | 0 |
| 21 | [50%] | 189 | 0 |
| 22 | [50%] | 176 | 0 |
| 23 | [50%] | 180 | 0 |
| 24 | [50%] | 174 | 0 |

### E.6.6 *Hourly LCA Optimization Model* for min $SO_2$ in a day in June

**Table 6-76: Supply from the energy systems in an average day in June (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 26 | 25 | 3 | 142 |
| 2 | 0 | 0 | 5 | 22 | 0 | 0 | 1 | 168 |
| 3 | 0 | 0 | 0 | 0 | 19 | 18 | 10 | 150 |
| 4 | 0 | 0 | 0 | 0 | 15 | 14 | 13 | 154 |
| 5 | 0 | 0 | 0 | 0 | 11 | 11 | 17 | 156 |
| 6 | 0 | 0 | 0 | 0 | 9 | 9 | 20 | 157 |
| 7 | 0 | 0 | 0 | 0 | 44 | 42 | 8 | 126 |
| 8 | 0 | 0 | 0 | 0 | 184 | 175 | 0 | 60 |
| 9 | 0 | 0 | 0 | 0 | 304 | 289 | 0 | 59 |
| 10 | 0 | 0 | 4 | 19 | 376 | 358 | 0 | 0 |
| 11 | 0 | 0 | 13 | 60 | 410 | 391 | 0 | 16 |
| 12 | 0 | 0 | 16 | 75 | 432 | 411 | 0 | 0 |

| Table 6-76 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 13 | 0 | 0 | 18 | 81 | 436 | 416 | 0 | 0 |
| 14 | 0 | 0 | 21 | 94 | 442 | 421 | 0 | 0 |
| 15 | 0 | 0 | 22 | 103 | 445 | 424 | 0 | 0 |
| 16 | 0 | 0 | 27 | 122 | 452 | 430 | 0 | 0 |
| 17 | 0 | 0 | 25 | 114 | 449 | 427 | 0 | 0 |
| 18 | 0 | 0 | 18 | 84 | 411 | 391 | 0 | 0 |
| 19 | 0 | 0 | 34 | 156 | 255 | 243 | 0 | 0 |
| 20 | 0 | 0 | 16 | 73 | 191 | 182 | 0 | 25 |
| 21 | 0 | 0 | 0 | 0 | 124 | 118 | 0 | 72 |
| 22 | 0 | 0 | 0 | 0 | 64 | 61 | 0 | 113 |
| 23 | 0 | 0 | 0 | 0 | 44 | 42 | 0 | 137 |
| 24 | 0 | 0 | 0 | 0 | 34 | 32 | 0 | 138 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |

**P_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 3 | [50%] | 76 | 0 |
| 4 | [50%] | 76 | 0 |
| 5 | [50%] | 76 | 0 |
| 6 | [50%] | 76 | 0 |
| 7 | [50%] | 76 | 0 |
| 8 | [100%] | 153 | 0 |
| 9 | [100%] | 163 | 0 |
| 10 | [100%] | 169 | 0 |
| 11 | [100%], [50%] | 151 [100%] | 76 [50%] |
| 12 | [100%], [50%] | 155 [100%] | 76 [50%] |
| 13 | [100%], [50%] | 157 [100%] | 76 [50%] |
| 14 | [100%], [50%] | 160 [100%] | 76 [50%] |
| 15 | [100%], [50%] | 161 [100%] | 76 [50%] |
| 16 | [100%], [50%] | 167 [100%] | 76 [50%] |
| 17 | [100%], [50%] | 165 [100%] | 76 [50%] |
| 18 | [75%], [50%] | 121 [100%] | 76 [50%] |
| 19 | [100%] | 154 | 0 |
| 20 | [75%] | 113 | 0 |
| 21 | [50%] | 86 | 0 |
| 22 | [50%] | 79 | 0 |
| 23 | [50%] | 81 | 0 |
| 24 | [50%] | 77 | 0 |

**H_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |

| Table 6-76 (continued) | | | |
|---|---|---|---|
| 3 | [50%] | 174 | 0 |
| 4 | [50%] | 174 | 0 |
| 5 | [50%] | 174 | 0 |
| 6 | [50%] | 174 | 0 |
| 7 | [50%] | 174 | 0 |
| 8 | [100%] | 251 | 0 |
| 9 | [100%] | 268 | 0 |
| 10 | [100%] | 278 | 0 |
| 11 | [100%], [50%] | 248 [100%] | 174 [50%] |
| 12 | [100%], [50%] | 255 [100%] | 174 [50%] |
| 13 | [100%], [50%] | 257 [100%] | 174 [50%] |
| 14 | [100%], [50%] | 262 [100%] | 174 [50%] |
| 15 | [100%], [50%] | 265 [100%] | 174 [50%] |
| 16 | [100%], [50%] | 274 [100%] | 174 [50%] |
| 17 | [100%], [50%] | 271 [100%] | 174 [50%] |
| 18 | [75%], [50%] | 231 [100%] | 174 [50%] |
| 19 | [100%] | 253 | 0 |
| 20 | [75%] | 215 | 0 |
| 21 | [50%] | 196 | 0 |
| 22 | [50%] | 180 | 0 |
| 23 | [50%] | 185 | 0 |
| 24 | [50%] | 176 | 0 |

### E.6.7 *Hourly LCA Optimization Model* for min $SO_2$ in a day in July

**Table 6-77: Supply from the energy systems in an average day in July (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 60 | 57 | 1 | 110 |
| 2 | 0 | 0 | 0 | 0 | 52 | 50 | 5 | 118 |
| 3 | 0 | 0 | 0 | 0 | 45 | 43 | 8 | 125 |
| 4 | 0 | 0 | 0 | 0 | 38 | 36 | 12 | 131 |
| 5 | 0 | 0 | 0 | 0 | 31 | 30 | 16 | 138 |
| 6 | 0 | 0 | 0 | 0 | 27 | 26 | 19 | 142 |
| 7 | 0 | 0 | 0 | 0 | 64 | 61 | 7 | 106 |
| 8 | 0 | 0 | 0 | 0 | 236 | 225 | 0 | 20 |
| 9 | 0 | 0 | 0 | 0 | 372 | 354 | 0 | 8 |
| 10 | 0 | 0 | 11 | 49 | 434 | 413 | 0 | 0 |
| 11 | 0 | 0 | 25 | 113 | 462 | 440 | 0 | 0 |
| 12 | 0 | 0 | 35 | 162 | 486 | 463 | 0 | 0 |
| 13 | 0 | 0 | 45 | 207 | 476 | 454 | 0 | 0 |
| 14 | 0 | 0 | 48 | 218 | 480 | 457 | 0 | 0 |
| 15 | 0 | 0 | 52 | 240 | 489 | 466 | 0 | 0 |

| Table 6-77 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 16 | 0 | 0 | 58 | 264 | 498 | 475 | 0 | 0 |
| 17 | 0 | 0 | 57 | 260 | 497 | 473 | 0 | 0 |
| 18 | 0 | 0 | 49 | 223 | 441 | 420 | 0 | 0 |
| 19 | 0 | 0 | 37 | 169 | 384 | 365 | 0 | 0 |
| 20 | 0 | 0 | 25 | 113 | 245 | 233 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 192 | 183 | 0 | 16 |
| 22 | 0 | 0 | 0 | 0 | 119 | 114 | 0 | 68 |
| 23 | 0 | 0 | 0 | 0 | 91 | 87 | 0 | 97 |
| 24 | 0 | 0 | 0 | 0 | 74 | 70 | 0 | 104 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |

**P_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 3 | [50%] | 76 | 0 |
| 4 | [50%] | 76 | 0 |
| 5 | [50%] | 76 | 0 |
| 6 | [50%] | 76 | 0 |
| 7 | [50%] | 76 | 0 |
| 8 | [100%] | 159 | 0 |
| 9 | [100%] | 172 | 0 |
| 10 | [100%] | 156 | 76 [50%] |
| 11 | [100%], [50%] | 172 | 76 [50%] |
| 12 | [100%], [50%] | 172 | 86 [50%] |
| 13 | [100%], [75%] | 155 | 113 [75%] |
| 14 | [100%], [75%] | 158 | 113 [75%] |
| 15 | [100%], [75%] | 162 | 113 [75%] |
| 16 | [100%], [75%] | 169 | 113 [75%] |
| 17 | [100%], [75%] | 168 | 113 [75%] |
| 18 | [100%], [50%] | 159 | 76 [50%] |
| 19 | [50%] | 82 | 82 |
| 20 | [75%] | 127 | 0 |
| 21 | [50%] | 90 | 0 |
| 22 | [50%] | 82 | 0 |
| 23 | [50%] | 83 | 0 |
| 24 | [50%] | 79 | 0 |

**H_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 3 | [50%] | 174 | 0 |
| 4 | [50%] | 174 | 0 |
| 5 | [50%] | 174 | 0 |
| 6 | [50%] | 174 | 0 |

| Table 6-77 (continued) | | | |
|---|---|---|---|
| 7 | [50%] | 174 | 0 |
| 8 | [100%] | 261 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 256 | 174 [50%] |
| 11 | [100%], [50%] | 282 | 174 [50%] |
| 12 | [100%], [50%] | 282 | 197 [50%] |
| 13 | [100%], [75%] | 255 | 215 [75%] |
| 14 | [100%], [75%] | 259 | 215 [75%] |
| 15 | [100%], [75%] | 267 | 215 [75%] |
| 16 | [100%], [75%] | 277 | 215 [75%] |
| 17 | [100%], [75%] | 275 | 215 [75%] |
| 18 | [100%], [50%] | 260 | 174 [50%] |
| 19 | [50%] | 188 | 188 |
| 20 | [75%] | 241 | 0 |
| 21 | [50%] | 205 | 0 |
| 22 | [50%] | 187 | 0 |
| 23 | [50%] | 189 | 0 |
| 24 | [50%] | 180 | 0 |

### E.6.8 *Hourly LCA Optimization Model* for min $SO_2$ in a day in August

**Table 6-78: Supply from the energy systems in an average day in August (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 49 | 47 | 2 | 121 |
| 2 | 0 | 0 | 0 | 0 | 40 | 38 | 5 | 129 |
| 3 | 0 | 0 | 0 | 0 | 34 | 32 | 9 | 135 |
| 4 | 0 | 0 | 0 | 0 | 29 | 27 | 12 | 140 |
| 5 | 0 | 0 | 0 | 0 | 25 | 23 | 16 | 144 |
| 6 | 0 | 0 | 0 | 0 | 22 | 21 | 19 | 147 |
| 7 | 0 | 0 | 0 | 0 | 33 | 32 | 8 | 136 |
| 8 | 0 | 0 | 0 | 0 | 189 | 180 | 0 | 62 |
| 9 | 0 | 0 | 0 | 0 | 343 | 326 | 0 | 36 |
| 10 | 0 | 0 | 7 | 31 | 429 | 408 | 0 | 0 |
| 11 | 0 | 0 | 23 | 108 | 459 | 437 | 0 | 0 |
| 12 | 0 | 0 | 32 | 146 | 480 | 457 | 0 | 0 |
| 13 | 0 | 0 | 40 | 183 | 468 | 446 | 0 | 1 |
| 14 | 0 | 0 | 44 | 200 | 474 | 451 | 0 | 0 |
| 15 | 0 | 0 | 48 | 220 | 483 | 460 | 0 | 0 |
| 16 | 0 | 0 | 52 | 239 | 489 | 466 | 0 | 0 |
| 17 | 0 | 0 | 49 | 224 | 483 | 460 | 0 | 0 |
| 18 | 0 | 0 | 42 | 192 | 396 | 377 | 0 | 30 |
| 19 | 0 | 0 | 40 | 182 | 271 | 258 | 0 | 0 |
| 20 | 0 | 0 | 16 | 73 | 181 | 172 | 0 | 35 |

Table 6-78 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 21 | 0 | 0 | 0 | 0 | 132 | 126 | 0 | 67 |
| 22 | 0 | 0 | 0 | 0 | 84 | 80 | 0 | 97 |
| 23 | 0 | 0 | 0 | 0 | 65 | 62 | 0 | 119 |
| 24 | 0 | 0 | 0 | 0 | 55 | 53 | 0 | 120 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |

**P_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 3 | [50%] | 76 | 0 |
| 4 | [50%] | 76 | 0 |
| 5 | [50%] | 76 | 0 |
| 6 | [50%] | 76 | 0 |
| 7 | [50%] | 76 | 0 |
| 8 | [100%] | 158 | 0 |
| 9 | [100%] | 172 | 0 |
| 10 | [100%] | 153 | 76 [50%] |
| 11 | [100%], [50%] | 170 | 76 [50%] |
| 12 | [100%], [50%] | 172 | 84 [50%] |
| 13 | [100%], [75%] | 151 | 113 [75%] |
| 14 | [100%], [75%] | 154 | 113 [75%] |
| 15 | [100%], [75%] | 159 | 113 [75%] |
| 16 | [100%], [75%] | 163 | 113 [75%] |
| 17 | [100%], [75%] | 160 | 113 [75%] |
| 18 | [100%], [50%] | 151 | 76 [50%] |
| 19 | [100%] | 164 | |
| 20 | [75%] | 113 | 0 |
| 21 | [50%] | 87 | 0 |
| 22 | [50%] | 80 | 0 |
| 23 | [50%] | 82 | 0 |
| 24 | [50%] | 78 | 0 |

**P_ICE**

| Hour | MT No. / Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 3 | [50%] | 174 | 0 |
| 4 | [50%] | 174 | 0 |
| 5 | [50%] | 174 | 0 |
| 6 | [50%] | 174 | 0 |
| 7 | [50%] | 174 | 0 |
| 8 | [100%] | 259 | 0 |
| 9 | [100%] | 282 | 0 |
| 10 | [100%] | 251 | 174 [50%] |
| 11 | [100%], [50%] | 280 | 174 [50%] |

| Table 6-78 (continued) | | | |
|---|---|---|---|
| 12 | [100%], [50%] | 282 | 192 [50%] |
| 13 | [100%], [75%] | 248 | 215 [75%] |
| 14 | [100%], [75%] | 252 | 215 [75%] |
| 15 | [100%], [75%] | 261 | 215 [75%] |
| 16 | [100%], [75%] | 268 | 215 [75%] |
| 17 | [100%], [75%] | 263 | 215 [75%] |
| 18 | [100%], [50%] | 248 | 174 [50%] |
| 19 | [100%] | 269 | 0 |
| 20 | [75%] | 215 | 0 |
| 21 | [50%] | 199 | 0 |
| 22 | [50%] | 183 | 0 |
| 23 | [50%] | 187 | 0 |
| 24 | [50%] | 178 | 0 |

### E.6.9 *Hourly LCA Optimization Model* for min $SO_2$ in a day in September

**Table 6-79: Supply from the energy systems in an average day in September (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 16 | 15 | 3 | 152 |
| 2 | 0 | 0 | 0 | 0 | 12 | 12 | 7 | 156 |
| 3 | 0 | 0 | 0 | 0 | 10 | 9 | 10 | 157 |
| 4 | 0 | 0 | 0 | 0 | 7 | 7 | 13 | 157 |
| 5 | 0 | 0 | 0 | 0 | 6 | 5 | 17 | 156 |
| 6 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 122 |
| 7 | 0 | 0 | 0 | 0 | 8 | 7 | 10 | 148 |
| 8 | 0 | 0 | 0 | 0 | 79 | 75 | 0 | 155 |
| 9 | 0 | 0 | 0 | 0 | 173 | 165 | 0 | 182 |
| 10 | 0 | 0 | 0 | 0 | 284 | 271 | 0 | 81 |
| 11 | 0 | 0 | 1 | 6 | 373 | 355 | 0 | 0 |
| 12 | 0 | 0 | 12 | 55 | 375 | 357 | 0 | 47 |
| 13 | 0 | 0 | 9 | 41 | 427 | 406 | 2 | 0 |
| 14 | 0 | 0 | 14 | 62 | 431 | 411 | 0 | 0 |
| 15 | 0 | 0 | 18 | 84 | 439 | 418 | 0 | 0 |
| 16 | 0 | 0 | 22 | 99 | 443 | 422 | 0 | 0 |
| 17 | 0 | 0 | 16 | 71 | 433 | 412 | 0 | 0 |
| 18 | 0 | 0 | 11 | 51 | 338 | 322 | 0 | 0 |
| 19 | 0 | 0 | 6 | 28 | 229 | 218 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 | 122 | 116 | 0 | 81 |
| 21 | 0 | 0 | 0 | 0 | 65 | 62 | 0 | 122 |
| 22 | 0 | 0 | 0 | 0 | 36 | 34 | 0 | 136 |
| 23 | 0 | 0 | 0 | 0 | 25 | 24 | 0 | 153 |
| 24 | 0 | 0 | 0 | 0 | 20 | 19 | 0 | 148 |

Table 6-79 (continued)

| **Hour** | **MT No.** Part Load | **P_MT** | **H_MT** |
|---|---|---|---|
| 6 | [75%], [50%] | 35 [75%] (unit 1)<br>21 [50%] (unit 2) | 83 [75%] (unit 1)<br>58 [50%] (unit 2) |
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 18 | [50%] | 21 | 58 |

**P_ICE**

| Hour | MT No. Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 76 | 0 |
| 2 | [50%] | 76 | 0 |
| 3 | [50%] | 76 | 0 |
| 4 | [50%] | 76 | 0 |
| 5 | [50%] | 76 | 0 |
| 7 | [50%] | 76 | 0 |
| 8 | [100%] | 152 | 0 |
| 9 | [100%] | 162 | 0 |
| 10 | [100%] | 165 | 0 |
| 11 | [100%] | 167 | 0 |
| 12 | [100%], [50%] | 151 | 76 [50%] |
| 13 | [100%], [50%] | 151 | 76 [50%] |
| 14 | [100%], [50%] | 154 | 76 [50%] |
| 15 | [100%], [50%] | 158 | 76 [50%] |
| 16 | [100%], [50%] | 162 | 76 [50%] |
| 17 | [100%], [50%] | 156 | 76 [50%] |
| 18 | [100%] | 169 | 0 |
| 19 | [75%] | 120 | 0 |
| 20 | [50%] | 90 | 0 |
| 21 | [50%] | 83 | 0 |
| 22 | [50%] | 77 | 0 |
| 23 | [50%] | 80 | 0 |
| 24 | [50%] | 76 | 0 |

**H_ICE**

| Hour | MT No. Part Load | 1 | 2 |
|---|---|---|---|
| 1 | [50%] | 174 | 0 |
| 2 | [50%] | 174 | 0 |
| 3 | [50%] | 174 | 0 |
| 4 | [50%] | 174 | 0 |
| 5 | [50%] | 174 | 0 |
| 7 | [50%] | 174 | 0 |
| 8 | [100%] | 250 | 0 |
| 9 | [100%] | 266 | 0 |
| 10 | [100%] | 271 | 0 |
| 11 | [100%] | 275 | 0 |

| Table 6-79 (continued) | | | |
|---|---|---|---|
| 12 | [100%], [50%] | 248 | 174 [50%] |
| 13 | [100%], [50%] | 248 | 174 [50%] |
| 14 | [100%], [50%] | 252 | 174 [50%] |
| 15 | [100%], [50%] | 260 | 174 [50%] |
| 16 | [100%], [50%] | 265 | 174 [50%] |
| 17 | [100%], [50%] | 255 | 174 [50%] |
| 18 | [100%] | 277 | 0 |
| 19 | [75%] | 228 | 0 |
| 20 | [50%] | 205 | 0 |
| 21 | [50%] | 189 | 0 |
| 22 | [50%] | 176 | 0 |
| 23 | [50%] | 183 | 0 |
| 24 | [50%] | 174 | 0 |

### E.6.10 *Hourly LCA Optimization Model* for min $SO_2$ in a day in October

**Table 6-80: Supply from the energy systems in an average day in October (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 118 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 105 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 90 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 78 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 64 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 51 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 49 |
| 8 | 0 | 0 | 0 | 0 | 3 | 2 | 0 | 143 |
| 9 | 0 | 0 | 0 | 0 | 24 | 23 | 0 | 318 |
| 10 | 0 | 0 | 0 | 0 | 107 | 102 | 0 | 254 |
| 11 | 0 | 0 | 0 | 0 | 208 | 198 | 0 | 159 |
| 12 | 0 | 0 | 0 | 0 | 280 | 267 | 0 | 93 |
| 13 | 0 | 0 | 0 | 0 | 321 | 306 | 0 | 55 |
| 14 | 0 | 0 | 0 | 0 | 351 | 335 | 0 | 27 |
| 15 | 0 | 0 | 0 | 0 | 376 | 358 | 0 | 6 |
| 16 | 0 | 0 | 0 | 0 | 372 | 355 | 0 | 6 |
| 17 | 0 | 0 | 0 | 0 | 324 | 308 | 0 | 51 |
| 18 | 0 | 0 | 0 | 0 | 224 | 214 | 0 | 95 |
| 19 | 0 | 0 | 0 | 0 | 70 | 67 | 6 | 137 |
| 20 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 171 |
| 21 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 172 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 158 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 151 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 132 |

Table 6-80 (continued)

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |
| 15 | [100%] | 48 | 96 |
| 16 | [100%] | 48 | 96 |
| 17 | [100%] | 48 | 96 |
| 18 | [25%] | 9 | 40 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 1 | [50%] | 76 | 174 |
| 2 | [50%] | 76 | 174 |
| 3 | [50%] | 76 | 174 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |
| 8 | [100%] | 156 | 256 |
| 9 | [100%] | 167 | 274 |
| 10 | [100%] | 168 | 276 |
| 11 | [100%] | 169 | 278 |
| 12 | [100%] | 171 | 281 |
| 13 | [100%] | 171 | 281 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 171 | 281 |
| 18 | [100%] | 172 | 282 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 85 | 194 |
| 21 | [50%] | 80 | 183 |
| 22 | [50%] | 76 | 174 |
| 23 | [50%] | 79 | 180 |
| 24 | [50%] | 77 | 176 |

### E.6.11 *Hourly LCA Optimization Model* for min $SO_2$ in a day in November

**Table 6-81: Supply from the energy systems in an average day in November (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 46 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 61 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 75 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 83 | 0 | 0 | 0 | 0 | 3 | 0 |
| 5 | 0 | 90 | 0 | 0 | 0 | 0 | 6 | 0 |
| 6 | 0 | 97 | 0 | 0 | 0 | 0 | 9 | 0 |
| 7 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 26 |
| 9 | 0 | 0 | 0 | 0 | 12 | 11 | 0 | 237 |
| 10 | 0 | 0 | 0 | 0 | 40 | 38 | 0 | 263 |
| 11 | 0 | 0 | 0 | 0 | 67 | 63 | 0 | 259 |
| 12 | 0 | 0 | 0 | 0 | 106 | 101 | 0 | 228 |
| 13 | 0 | 0 | 0 | 0 | 137 | 131 | 0 | 200 |
| 14 | 0 | 0 | 0 | 0 | 157 | 149 | 0 | 186 |
| 15 | 0 | 0 | 0 | 0 | 168 | 160 | 0 | 166 |
| 16 | 0 | 0 | 0 | 0 | 141 | 134 | 0 | 178 |
| 17 | 0 | 0 | 0 | 0 | 76 | 73 | 0 | 220 |
| 18 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 178 |
| 19 | 0 | 0 | 0 | 0 | 2 | 2 | 13 | 131 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 77 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 35 |
| 22 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 9 | [75%] | 34 | 79 |
| 10 | [75%] | 34 | 79 |
| 11 | [75%] | 34 | 79 |
| 12 | [75%] | 34 | 79 |
| 13 | [75%] | 34 | 79 |
| 14 | [75%] | 34 | 79 |
| 15 | [75%] | 34 | 79 |
| 16 | [75%] | 34 | 79 |
| 17 | [75%] | 34 | 79 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |

| Table 6-81 (continued) | | | |
|---|---|---|---|
| 3 | [50%] | 76 | 174 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |
| 8 | [100%] | 151 | 248 |
| 9 | [100%] | 170 | 279 |
| 10 | [100%] | 169 | 278 |
| 11 | [100%] | 169 | 278 |
| 12 | [100%] | 170 | 279 |
| 13 | [100%] | 170 | 279 |
| 14 | [100%] | 171 | 281 |
| 15 | [100%] | 171 | 281 |
| 16 | [100%] | 170 | 279 |
| 17 | [100%] | 169 | 278 |
| 18 | [100%] | 168 | 276 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 86 | 196 |
| 21 | [50%] | 85 | 194 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 88 | 201 |
| 24 | [50%] | 85 | 194 |

### E.6.12 *Hourly LCA Optimization Model* for min $SO_2$ in a day in December

**Table 6-82: Supply from the energy systems in an average day in December (Hourly model: min $SO_2$).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 178 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 194 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 210 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 223 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 235 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 244 | 0 | 0 | 0 | 0 | 2 | 0 |
| 7 | 0 | 217 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 83 |
| 10 | 0 | 0 | 0 | 0 | 5 | 4 | 0 | 174 |
| 11 | 0 | 0 | 0 | 0 | 15 | 15 | 0 | 221 |
| 12 | 0 | 0 | 0 | 0 | 29 | 28 | 0 | 237 |
| 13 | 0 | 0 | 0 | 0 | 57 | 55 | 0 | 220 |
| 14 | 0 | 0 | 0 | 0 | 78 | 75 | 0 | 209 |
| 15 | 0 | 0 | 0 | 0 | 81 | 77 | 0 | 210 |
| 16 | 0 | 0 | 0 | 0 | 52 | 49 | 0 | 222 |

Table 6-82 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 17 | 0 | 0 | 0 | 0 | 16 | 15 | 0 | 207 |
| 18 | 0 | 0 | 0 | 0 | 6 | 6 | 0 | 107 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 17 |
| 20 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 133 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 139 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 9 | [100%] | 48 | 96 |
| 10 | [100%] | 48 | 96 |
| 11 | [100%] | 48 | 96 |
| 12 | [100%] | 48 | 96 |
| 13 | [100%] | 48 | 96 |
| 14 | [100%] | 48 | 96 |
| 15 | [100%] | 48 | 96 |
| 16 | [100%] | 48 | 96 |
| 17 | [100%] | 48 | 96 |
| 18 | [25%] | 9 | 40 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 77 | 176 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 82 (unit 1)<br>76 (unit 2) | 187 (unit 1)<br>174 (unit 2) |
| 9 | [100%] | 165 | 271 |
| 10 | [100%] | 164 | 269 |
| 11 | [100%] | 163 | 268 |
| 12 | [100%] | 163 | 268 |
| 13 | [100%] | 163 | 268 |
| 14 | [100%] | 164 | 269 |
| 15 | [100%] | 165 | 271 |
| 16 | [100%] | 164 | 269 |
| 17 | [100%] | 163 | 268 |
| 18 | [100%] | 166 | 273 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 94 | 215 |
| 21 | [50%] | 92 | 210 |
| 22 | [50%] | 90 | 205 |
| 23 | [50%] | 94 | 215 |
| 24 | [50%] | 91 | 208 |

## E.7 AVERAGE ELECTRIC OPTION: MIN PE

### E.7.1 *Hourly LCA Optimization Model* for min PE in a day in January

**Table 6-83: Supply from the energy systems in an average day in January (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 242 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 259 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 273 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 289 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 306 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 321 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 286 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 247 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 61 | 0 | 0 | 0 | 1 | 1 | 0 | 29 |
| 11 | 60 | 0 | 0 | 0 | 9 | 8 | 0 | 97 |
| 12 | 60 | 0 | 0 | 0 | 22 | 21 | 0 | 114 |
| 13 | 60 | 0 | 0 | 0 | 35 | 34 | 0 | 119 |
| 14 | 60 | 0 | 0 | 0 | 54 | 51 | 0 | 115 |
| 15 | 60 | 0 | 0 | 0 | 70 | 67 | 0 | 92 |
| 16 | 61 | 0 | 0 | 0 | 63 | 60 | 0 | 72 |
| 17 | 61 | 0 | 0 | 0 | 28 | 27 | 0 | 55 |
| 18 | 18 | 0 | 0 | 0 | 2 | 1 | 0 | 0 |
| 19 | 0 | 52 | 0 | 0 | 0 | 0 | 3 | 0 |
| 20 | 0 | 110 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 1 | 209 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 231 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 9 | [75%] | 34 | 79 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 1 | [50%] | 92 | 210 |
| 2 | [50%] | 89 | 203 |
| 3 | [50%] | 87 | 199 |
| 4 | [50%] | 84 | 192 |
| 5 | [50%] | 81 | 185 |

| Table 6-83 (continued) | | | |
|---|---|---|---|
| 6 | [50%] | 78 | 178 |
| 7 | [50%] | 88 | 201 |
| 8 | [100%] | 160 | 263 |
| 9 | [100%] | 156 | 256 |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 151 | 248 |
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 151 | 248 |
| 15 | [100%] | 151 | 248 |
| 16 | [100%] | 151 | 248 |
| 17 | [100%] | 151 | 248 |
| 18 | [100%] | 159 | 261 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 97 | 221 |
| 21 | [50%] | 95 | 217 |
| 22 | [50%] | 93 | 212 |
| 23 | [50%] | 97 | 221 |
| 24 | [50%] | 95 | 217 |

### E.7.2 *Hourly LCA Optimization Model* for min PE in a day in February

**Table 6-84: Supply from the energy systems in an average day in February (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 177 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 214 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 232 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 248 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 263 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 229 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 129 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 61 | 0 | 0 | 0 | 0 | 0 | 0 | 16 |
| 10 | 61 | 0 | 0 | 0 | 21 | 20 | 0 | 93 |
| 11 | 61 | 0 | 0 | 0 | 41 | 39 | 0 | 115 |
| 12 | 61 | 0 | 0 | 0 | 64 | 61 | 0 | 119 |
| 13 | 61 | 0 | 0 | 0 | 86 | 82 | 0 | 117 |
| 14 | 61 | 0 | 0 | 0 | 97 | 92 | 0 | 109 |
| 15 | 61 | 0 | 0 | 0 | 121 | 116 | 0 | 80 |
| 16 | 61 | 0 | 0 | 0 | 120 | 114 | 0 | 67 |
| 17 | 61 | 0 | 0 | 0 | 97 | 92 | 0 | 74 |
| 18 | 25 | 0 | 0 | 0 | 27 | 26 | 0 | 95 |
| 19 | 29 | 0 | 0 | 0 | 1 | 1 | 0 | 30 |

| Table 6-84 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 20 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 39 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 118 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 127 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 78 | 178 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [100%] | 157 | 258 |
| 9 | [100%] | 151 | 248 |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 151 | 248 |
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 151 | 248 |
| 15 | [100%] | 151 | 248 |
| 16 | [100%] | 151 | 248 |
| 17 | [100%] | 151 | 248 |
| 18 | [100%] | 151 | 248 |
| 19 | [50%] | 76 | 174 |
| 20 | [50%] | 84 | 191 |
| 21 | [50%] | 89 | 203 |
| 22 | [50%] | 88 | 201 |
| 23 | [50%] | 93 | 212 |
| 24 | [50%] | 91 | 208 |

### E.7.3 *Hourly LCA Optimization Model* for min PE in a day in March

**Table 6-85: Supply from the energy systems in an average day in March (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 54 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 74 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 92 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 109 | 0 | 0 | 0 | 0 | 2 | 0 |
| 5 | 0 | 118 | 0 | 0 | 0 | 0 | 5 | 0 |
| 6 | 0 | 127 | 0 | 0 | 0 | 0 | 8 | 0 |
| 7 | 0 | 99 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6-85 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 8 | 3 | 0 | 0 | 0 | 1 | 1 | 0 | 8 |
| 9 | 60 | 0 | 0 | 0 | 35 | 33 | 0 | 88 |
| 10 | 61 | 0 | 0 | 0 | 86 | 82 | 0 | 85 |
| 11 | 62 | 0 | 0 | 0 | 131 | 124 | 0 | 66 |
| 12 | 63 | 0 | 0 | 0 | 156 | 149 | 0 | 50 |
| 13 | 63 | 0 | 0 | 0 | 178 | 170 | 0 | 39 |
| 14 | 64 | 0 | 0 | 0 | 209 | 199 | 0 | 13 |
| 15 | 63 | 0 | 0 | 0 | 222 | 211 | 0 | 0 |
| 16 | 58 | 0 | 0 | 0 | 224 | 214 | 0 | 0 |
| 17 | 63 | 0 | 0 | 0 | 180 | 171 | 0 | 22 |
| 18 | 25 | 0 | 0 | 0 | 102 | 97 | 0 | 78 |
| 19 | 56 | 0 | 0 | 0 | 25 | 24 | 0 | 4 |
| 20 | 35 | 0 | 0 | 0 | 8 | 7 | 0 | 0 |
| 21 | 9 | 0 | 0 | 0 | 3 | 3 | 0 | 36 |
| 22 | 4 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 23 | 0 | 7 | 0 | 1 | 0 | 0 | 0 | 0 |
| 24 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 19 | [100%] | 48 | 96 |
| 20 | [100%] | 52 | 104 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 77 | 176 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 77 | 176 |
| 8 | [100%] | 151 | 248 |
| 9 | [100%] | 151 | 248 |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 151 | 248 |
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 151 | 248 |
| 15 | [100%] | 152 | 249 |
| 16 | [100%] | 157 | 258 |
| 17 | [100%] | 151 | 248 |
| 18 | [100%] | 151 | 248 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 76 | 174 |
| 21 | [50%] | 79 | 180 |
| 22 | [50%] | 87 | 199 |
| 23 | [50%] | 85 | 194 |
| 24 | [50%] | 95 | 217 |

## E.7.4 *Hourly LCA Optimization Model* for min PE in a day in April

**Table 6-86: Supply from the energy systems in an average day in April (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 22 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 33 | 0 | 0 | 0 | 0 | 4 | 0 |
| 3 | 0 | 50 | 0 | 0 | 0 | 0 | 7 | 0 |
| 4 | 0 | 65 | 0 | 0 | 0 | 0 | 9 | 0 |
| 5 | 0 | 81 | 0 | 0 | 0 | 0 | 12 | 0 |
| 6 | 0 | 98 | 0 | 0 | 0 | 0 | 15 | 0 |
| 7 | 0 | 78 | 0 | 0 | 0 | 0 | 4 | 0 |
| 8 | 40 | 1 | 0 | 2 | 0 | 0 | 0 | 0 |
| 9 | 100 | 0 | 0 | 0 | 45 | 43 | 0 | 6 |
| 10 | 0 | 0 | 0 | 0 | 125 | 119 | 5 | 141 |
| 11 | 0 | 0 | 0 | 0 | 193 | 184 | 4 | 79 |
| 12 | 0 | 0 | 0 | 0 | 246 | 234 | 3 | 28 |
| 13 | 0 | 0 | 2 | 7 | 267 | 254 | 0 | 8 |
| 14 | 0 | 0 | 7 | 30 | 284 | 271 | 0 | 0 |
| 15 | 0 | 0 | 10 | 48 | 293 | 279 | 0 | 0 |
| 16 | 0 | 0 | 12 | 57 | 295 | 281 | 0 | 0 |
| 17 | 0 | 0 | 10 | 45 | 289 | 275 | 0 | 0 |
| 18 | 0 | 0 | 6 | 30 | 242 | 230 | 0 | 0 |
| 19 | 11 | 0 | 19 | 85 | 69 | 65 | 0 | 0 |
| 20 | 0 | 0 | 5 | 21 | 41 | 39 | 0 | 0 |
| 21 | 1 | 0 | 0 | 0 | 16 | 16 | 0 | 2 |
| 22 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 7 |
| 23 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 7 |
| 24 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [93%] | 120 | 80 |
| 10 | [62%] | 75 | 31 |
| 11 | [62%] | 75 | 31 |
| 12 | [62%] | 75 | 31 |
| 13 | [62%] | 75 | 31 |
| 14 | [62%] | 75 | 31 |

| Table 6-86 (continued) | | | |
|---|---|---|---|
| 15 | [62%] | 75 | 31 |
| 16 | [62%] | 75 | 31 |
| 17 | [62%] | 75 | 31 |
| 18 | [62%] | 78 | 32 |
| 19 | [93%] | 120 | 80 |
| 20 | [78%] | 95 | 53 |
| 21 | [62%] | 81 | 33 |
| 22 | [62%] | 76 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [62%] | 77 | 32 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 151 | 248 |
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 156 | 256 |
| 15 | [100%] | 161 | 264 |
| 16 | [100%] | 163 | 267 |
| 17 | [100%] | 159 | 262 |
| 18 | [75%] | 113 | 215 |

## E.7.5 *Hourly LCA Optimization Model* for min PE in a day in May

**Table 6-87: Supply from the energy systems in an average day in May (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 7 | 7 | 3 | 15 |
| 2 | 0 | 0 | 0 | 0 | 5 | 5 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 3 | 3 | 9 | 11 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 12 | 8 |
| 5 | 0 | 0 | 0 | 0 | 1 | 1 | 16 | 5 |
| 6 | 0 | 0 | 0 | 1 | 0 | 0 | 18 | 0 |
| 7 | 0 | 0 | 0 | 0 | 7 | 7 | 8 | 3 |
| 8 | 37 | 0 | 0 | 0 | 62 | 59 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 163 | 155 | 8 | 107 |
| 10 | 0 | 0 | 0 | 0 | 255 | 243 | 7 | 20 |
| 11 | 0 | 0 | 10 | 46 | 284 | 270 | 0 | 0 |
| 12 | 0 | 0 | 16 | 74 | 295 | 281 | 0 | 0 |
| 13 | 0 | 0 | 19 | 88 | 301 | 287 | 0 | 0 |
| 14 | 0 | 0 | 23 | 107 | 302 | 288 | 0 | 0 |
| 15 | 0 | 0 | 27 | 122 | 308 | 293 | 0 | 0 |
| 16 | 0 | 0 | 29 | 132 | 311 | 296 | 0 | 0 |
| 17 | 0 | 0 | 25 | 114 | 302 | 288 | 0 | 0 |

Table 6-87 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 18 | 0 | 0 | 22 | 98 | 262 | 250 | 0 | 2 |
| 19 | 0 | 0 | 27 | 123 | 143 | 136 | 0 | 0 |
| 20 | 1 | 0 | 18 | 84 | 63 | 60 | 0 | 0 |
| 21 | 0 | 0 | 4 | 17 | 37 | 36 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 | 23 | 22 | 0 | 4 |
| 23 | 0 | 0 | 0 | 0 | 15 | 14 | 0 | 12 |
| 24 | 0 | 0 | 0 | 0 | 10 | 10 | 0 | 16 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [62%] | 75 | 31 |
| 10 | [62%] | 75 | 31 |
| 11 | [62%] | 75 | 31 |
| 12 | [62%] | 75 | 31 |
| 13 | [62%] | 75 | 31 |
| 14 | [78%] | 92 | 51 |
| 15 | [78%] | 92 | 51 |
| 16 | [78%] | 92 | 51 |
| 17 | [78%] | 92 | 51 |
| 18 | [78%] | 92 | 51 |
| 19 | [85%] | 111 | 68 |
| 20 | [85%] | 111 | 68 |
| 21 | [68%] | 87 | 42 |
| 22 | [62%] | 77 | 32 |
| 23 | [62%] | 79 | 33 |
| 24 | [62%] | 76 | 31 |

| **Hour** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 19 | [75%] | 34 | 79 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 9 | [100%] | 151 | 248 |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 156 | 255 |
| 12 | [100%] | 163 | 267 |
| 13 | [100%] | 166 | 272 |
| 14 | [100%] | 154 | 253 |
| 15 | [100%] | 157 | 258 |
| 16 | [100%] | 159 | 262 |
| 17 | [100%] | 154 | 253 |
| 18 | [75%] | 113 | 215 |

### E.7.6 *Hourly LCA Optimization Model* for min PE in a day in June

**Table 6-88: Supply from the energy systems in an average day in June (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 2 | 7 | 19 | 19 | 0 | 6 |
| 2 | 0 | 0 | 0 | 0 | 22 | 21 | 5 | 4 |
| 3 | 0 | 0 | 0 | 0 | 19 | 18 | 9 | 7 |
| 4 | 0 | 0 | 0 | 0 | 15 | 14 | 12 | 11 |
| 5 | 0 | 0 | 0 | 0 | 11 | 11 | 16 | 13 |
| 6 | 0 | 0 | 2 | 9 | 0 | 0 | 17 | 23 |
| 7 | 0 | 0 | 7 | 30 | 14 | 14 | 0 | 11 |
| 8 | 0 | 0 | 6 | 28 | 156 | 148 | 0 | 0 |
| 9 | 0 | 0 | 15 | 66 | 237 | 226 | 0 | 38 |
| 10 | 0 | 0 | 22 | 102 | 294 | 280 | 0 | 0 |
| 11 | 0 | 0 | 35 | 160 | 310 | 295 | 0 | 0 |
| 12 | 0 | 0 | 41 | 187 | 319 | 304 | 0 | 0 |
| 13 | 0 | 0 | 42 | 194 | 324 | 308 | 0 | 0 |
| 14 | 0 | 0 | 45 | 207 | 329 | 313 | 0 | 0 |
| 15 | 0 | 0 | 47 | 216 | 332 | 316 | 0 | 0 |
| 16 | 0 | 0 | 52 | 239 | 335 | 319 | 0 | 0 |
| 17 | 0 | 0 | 50 | 229 | 334 | 318 | 0 | 0 |
| 18 | 0 | 0 | 47 | 215 | 280 | 266 | 0 | 0 |
| 19 | 0 | 0 | 43 | 195 | 215 | 205 | 0 | 0 |
| 20 | 18 | 0 | 41 | 189 | 76 | 72 | 0 | 0 |
| 21 | 0 | 0 | 15 | 71 | 53 | 51 | 0 | 0 |
| 22 | 0 | 0 | 6 | 27 | 37 | 35 | 0 | 0 |
| 23 | 0 | 0 | 2 | 9 | 36 | 34 | 0 | 0 |
| 24 | 0 | 0 | 1 | 6 | 28 | 26 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [62%] | 75 | 31 |
| 10 | [62%] | 75 | 31 |
| 11 | [78%] | 92 | 51 |
| 12 | [78%] | 92 | 51 |
| 13 | [78%] | 92 | 51 |
| 14 | [78%] | 92 | 51 |
| 15 | [78%] | 92 | 51 |
| 16 | [78%] | 96 | 54 |

| Table 6-88 (continued) | | | |
|---|---|---|---|
| 17 | [78%] | 94 | 53 |
| 18 | [62%] | 75 | 31 |
| 19 | [68%] | 87 | 42 |
| 20 | [93%] | 120 | 80 |
| 21 | [78%] | 101 | 57 |
| 22 | [68%] | 85 | 41 |
| 23 | [68%] | 83 | 40 |
| 24 | [62%] | 78 | 32 |
| **Hour** | **Part Load** | **P_MT** | **H_MT** |
| 8 | [100%] | 48 | 96 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 9 | [100%] | 151 | 248 |
| 10 | [100%] | 161 | 264 |
| 11 | [100%] | 158 | 259 |
| 12 | [100%] | 164 | 270 |
| 13 | [100%] | 166 | 272 |
| 14 | [100%] | 169 | 277 |
| 15 | [100%] | 171 | 280 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 152 | 249 |
| 19 | [50%] | 76 | 174 |

### E.7.7 *Hourly LCA Optimization Model* for min PE in a day in July

**Table 6-89: Supply from the energy systems in an average day in July (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 7 | 31 | 29 | 27 | 0 | 0 |
| 2 | 0 | 0 | 6 | 25 | 27 | 25 | 0 | 0 |
| 3 | 0 | 0 | 7 | 30 | 15 | 15 | 0 | 10 |
| 4 | 0 | 0 | 8 | 38 | 0 | 0 | 2 | 25 |
| 5 | 0 | 0 | 7 | 31 | 0 | 0 | 8 | 25 |
| 6 | 0 | 0 | 6 | 27 | 0 | 0 | 12 | 25 |
| 7 | 0 | 0 | 8 | 37 | 27 | 26 | 0 | 0 |
| 8 | 0 | 0 | 6 | 27 | 209 | 199 | 0 | 0 |
| 9 | 0 | 0 | 17 | 77 | 295 | 281 | 0 | 0 |
| 10 | 0 | 0 | 35 | 162 | 321 | 306 | 0 | 0 |
| 11 | 0 | 0 | 51 | 235 | 340 | 323 | 0 | 0 |
| 12 | 0 | 0 | 63 | 289 | 359 | 342 | 0 | 0 |
| 13 | 0 | 0 | 70 | 319 | 364 | 347 | 0 | 0 |
| 14 | 4 | 0 | 73 | 334 | 364 | 347 | 0 | 0 |

Table 6-89 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 15 | 10 | 0 | 80 | 365 | 364 | 347 | 0 | 0 |
| 16 | 19 | 0 | 87 | 399 | 363 | 346 | 0 | 0 |
| 17 | 17 | 0 | 86 | 393 | 363 | 346 | 0 | 0 |
| 18 | 0 | 0 | 73 | 335 | 328 | 313 | 0 | 0 |
| 19 | 0 | 0 | 66 | 303 | 249 | 237 | 0 | 0 |
| 20 | 0 | 0 | 45 | 208 | 150 | 143 | 0 | 0 |
| 21 | 0 | 0 | 26 | 118 | 75 | 71 | 0 | 0 |
| 22 | 0 | 0 | 15 | 69 | 51 | 48 | 0 | 0 |
| 23 | 0 | 0 | 9 | 43 | 48 | 46 | 0 | 0 |
| 24 | 0 | 0 | 8 | 36 | 38 | 36 | 0 | 0 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 81 | 33 |
| 2 | [62%] | 77 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 77 | 32 |
| 8 | [68%] | 89 | 43 |
| 9 | [62%] | 75 | 31 |
| 10 | [78%] | 92 | 51 |
| 11 | [78%] | 102 | 57 |
| 12 | [93%] | 114 | 76 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 120 | 80 |
| 15 | [93%] | 120 | 80 |
| 16 | [93%] | 120 | 80 |
| 17 | [93%] | 120 | 80 |
| 18 | [78%] | 92 | 51 |
| 19 | [62%] | 81 | 33 |
| 20 | [78%] | 99 | 56 |
| 21 | [93%] | 116 | 77 |
| 22 | [78%] | 97 | 54 |
| 23 | [78%] | 92 | 52 |
| 24 | [68%] | 87 | 42 |
| **Hour** | **Part Load** | **P_MT** | **H_MT** |
| 20 | [100%] | 48 | 96 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 8 | [50%] | 76 | 174 |
| 9 | [100%] | 162 | 266 |
| 10 | [100%] | 165 | 271 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |

| Table 6-89 (continued) | | | |
|---|---|---|---|
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 168 | 275 |
| 19 | [75%] | 113 | 215 |

### E.7.8 *Hourly LCA Optimization Model* for min PE in a day in August

**Table 6-90: Supply from the energy systems in an average day in August (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 5 | 21 | 28 | 26 | 0 | 0 |
| 2 | 0 | 0 | 4 | 16 | 24 | 23 | 0 | 2 |
| 3 | 0 | 0 | 7 | 34 | 0 | 0 | 0 | 25 |
| 4 | 0 | 0 | 6 | 29 | 0 | 0 | 4 | 25 |
| 5 | 0 | 0 | 5 | 25 | 0 | 0 | 9 | 25 |
| 6 | 0 | 0 | 5 | 22 | 0 | 0 | 13 | 25 |
| 7 | 0 | 0 | 7 | 30 | 4 | 3 | 0 | 21 |
| 8 | 0 | 0 | 6 | 26 | 164 | 156 | 0 | 0 |
| 9 | 0 | 0 | 12 | 55 | 287 | 273 | 0 | 0 |
| 10 | 0 | 0 | 31 | 143 | 316 | 301 | 0 | 0 |
| 11 | 0 | 0 | 50 | 228 | 339 | 323 | 0 | 0 |
| 12 | 1 | 0 | 60 | 276 | 350 | 333 | 0 | 0 |
| 13 | 0 | 0 | 64 | 291 | 361 | 343 | 0 | 0 |
| 14 | 0 | 0 | 68 | 311 | 363 | 346 | 0 | 0 |
| 15 | 6 | 0 | 74 | 339 | 364 | 347 | 0 | 0 |
| 16 | 11 | 0 | 80 | 364 | 363 | 346 | 0 | 0 |
| 17 | 7 | 0 | 75 | 344 | 363 | 346 | 0 | 0 |
| 18 | 0 | 0 | 62 | 282 | 306 | 292 | 0 | 0 |
| 19 | 0 | 0 | 49 | 225 | 228 | 217 | 0 | 0 |
| 20 | 16 | 0 | 39 | 178 | 76 | 72 | 0 | 0 |
| 21 | 2 | 0 | 17 | 78 | 53 | 51 | 0 | 0 |
| 22 | 0 | 0 | 10 | 45 | 39 | 37 | 0 | 0 |
| 23 | 0 | 0 | 6 | 27 | 38 | 36 | 0 | 0 |
| 24 | 0 | 0 | 4 | 20 | 35 | 34 | 0 | 0 |

| Hour | Part Load | P_SOFC | H_SOFC |
|---|---|---|---|
| 1 | [62%] | 97 | 32 |
| 2 | [62%] | 77 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |

| Table 6-90 (continued) | | | |
|---|---|---|---|
| 9 | [62%] | 75 | 31 |
| 10 | [78%] | 92 | 51 |
| 11 | [78%] | 101 | 56 |
| 12 | [85%] | 111 | 68 |
| 13 | [93%] | 116 | 77 |
| 14 | [93%] | 119 | 79 |
| 15 | [93%] | 120 | 80 |
| 16 | [93%] | 120 | 80 |
| 17 | [93%] | 120 | 80 |
| 18 | [78%] | 92 | 51 |
| 19 | [78%] | 97 | 54 |
| 20 | [93%] | 120 | 80 |
| 21 | [78%] | 102 | 57 |
| 22 | [68%] | 90 | 43 |
| 23 | [68%] | 88 | 42 |
| 24 | [68%] | 82 | 40 |
| **Hour** | **Part Load** | **P_MT** | **H_MT** |
| 8 | [100%] | 53 | 105 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 9 | [100%] | 158 | 259 |
| 10 | [100%] | 162 | 266 |
| 11 | [100%] | 172 | 282 |
| 12 | [100%] | 172 | 282 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 15 | [100%] | 172 | 282 |
| 16 | [100%] | 172 | 282 |
| 17 | [100%] | 172 | 282 |
| 18 | [100%] | 155 | 255 |
| 19 | [50%] | 76 | 174 |

### E.7.9 *Hourly LCA Optimization Model* for min PE in a day in September

**Table 6-91: Supply from the energy systems in an average day in September (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 16 | 15 | 2 | 10 |
| 2 | 0 | 0 | 0 | 0 | 12 | 12 | 6 | 13 |
| 3 | 0 | 0 | 0 | 0 | 10 | 9 | 9 | 15 |
| 4 | 0 | 0 | 0 | 0 | 7 | 7 | 12 | 15 |
| 5 | 0 | 0 | 0 | 0 | 6 | 5 | 16 | 13 |
| 6 | 0 | 0 | 0 | 0 | 4 | 4 | 19 | 11 |
| 7 | 0 | 0 | 0 | 0 | 8 | 7 | 9 | 5 |

| Table 6-91 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 8 | 35 | 0 | 3 | 15 | 64 | 61 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 173 | 165 | 0 | 89 |
| 10 | 0 | 0 | 3 | 13 | 271 | 258 | 0 | 0 |
| 11 | 0 | 0 | 19 | 89 | 290 | 277 | 0 | 0 |
| 12 | 0 | 0 | 29 | 132 | 298 | 284 | 0 | 0 |
| 13 | 0 | 0 | 34 | 156 | 311 | 297 | 0 | 0 |
| 14 | 0 | 0 | 38 | 175 | 318 | 303 | 0 | 0 |
| 15 | 0 | 0 | 43 | 196 | 327 | 311 | 0 | 0 |
| 16 | 0 | 0 | 46 | 211 | 330 | 314 | 0 | 0 |
| 17 | 0 | 0 | 40 | 184 | 320 | 305 | 0 | 0 |
| 18 | 0 | 0 | 27 | 123 | 266 | 253 | 0 | 0 |
| 19 | 0 | 0 | 25 | 116 | 141 | 134 | 0 | 0 |
| 20 | 0 | 0 | 14 | 63 | 58 | 56 | 0 | 0 |
| 21 | 0 | 0 | 6 | 26 | 39 | 37 | 0 | 0 |
| 22 | 0 | 0 | 2 | 8 | 28 | 26 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 25 | 24 | 0 | 3 |
| 24 | 0 | 0 | 0 | 0 | 20 | 19 | 0 | 6 |

| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [93%] | 120 | 80 |
| 9 | [78%] | 97 | 54 |
| 10 | [78%] | 102 | 57 |
| 11 | [62%] | 75 | 31 |
| 12 | [78%] | 92 | 51 |
| 13 | [78%] | 92 | 51 |
| 14 | [78%] | 92 | 51 |
| 15 | [78%] | 92 | 51 |
| 16 | [78%] | 92 | 51 |
| 17 | [78%] | 92 | 51 |
| 18 | [78%] | 92 | 51 |
| 19 | [78%] | 102 | 57 |
| 20 | [85%] | 104 | 64 |
| 21 | [68%] | 89 | 43 |
| 22 | [62%] | 79 | 32 |
| 23 | [62%] | 80 | 33 |
| 24 | [62%] | 76 | 31 |
| Hour | Part Load | P_MT | H_MT |
| 19 | [73%] | 37 | 87 |
| | | | |

Table 6-91 (continued)

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 9 | [75%] | 113 | 215 |
| 10 | [75%] | 114 | 217 |
| 11 | [100%] | 159 | 261 |
| 12 | [100%] | 152 | 250 |
| 13 | [100%] | 159 | 260 |
| 14 | [100%] | 163 | 267 |
| 15 | [100%] | 167 | 275 |
| 16 | [100%] | 171 | 280 |
| 17 | [100%] | 165 | 270 |
| 18 | [75%] | 113 | 215 |

## E.7.10 *Hourly LCA Optimization Model* for min PE in a day in October

**Table 6-92: Supply from the energy systems in an average day in October (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 24 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 37 | 0 | 0 | 0 | 0 | 3 | 0 |
| 3 | 0 | 52 | 0 | 0 | 0 | 0 | 6 | 0 |
| 4 | 0 | 65 | 0 | 0 | 0 | 0 | 8 | 0 |
| 5 | 0 | 79 | 0 | 0 | 0 | 0 | 12 | 0 |
| 6 | 0 | 92 | 0 | 0 | 0 | 0 | 15 | 0 |
| 7 | 0 | 94 | 0 | 0 | 0 | 0 | 4 | 0 |
| 8 | 27 | 2 | 1 | 3 | 0 | 0 | 0 | 0 |
| 9 | 113 | 0 | 0 | 0 | 24 | 23 | 0 | 5 |
| 10 | 104 | 0 | 9 | 39 | 67 | 64 | 0 | 0 |
| 11 | 2 | 0 | 0 | 0 | 208 | 198 | 0 | 57 |
| 12 | 0 | 0 | 7 | 30 | 250 | 238 | 0 | 23 |
| 13 | 0 | 0 | 9 | 41 | 280 | 267 | 0 | 0 |
| 14 | 0 | 0 | 14 | 62 | 290 | 276 | 0 | 0 |
| 15 | 0 | 0 | 17 | 78 | 298 | 283 | 0 | 0 |
| 16 | 0 | 0 | 17 | 78 | 295 | 280 | 0 | 0 |
| 17 | 0 | 0 | 10 | 44 | 280 | 267 | 0 | 0 |
| 18 | 3 | 0 | 0 | 0 | 224 | 214 | 0 | 3 |
| 19 | 0 | 0 | 2 | 11 | 59 | 56 | 0 | 0 |
| 20 | 4 | 0 | 0 | 0 | 16 | 16 | 0 | 10 |
| 21 | 0 | 0 | 0 | 0 | 4 | 4 | 0 | 22 |
| 22 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 16 |
| 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| 24 | 0 | 12 | 0 | 0 | 0 | 0 | 0 | 0 |

| Table 6-92 (continued) | | | |
|---|---|---|---|
| **Hour** | **Part Load** | **P_SOFC** | **H_SOFC** |
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [62%] | 75 | 31 |
| 4 | [62%] | 75 | 31 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [104%] | 130 | 109 |
| 9 | [78%] | 102 | 57 |
| 10 | [93%] | 120 | 80 |
| 11 | [78%] | 102 | 57 |
| 12 | [62%] | 75 | 31 |
| 13 | [62%] | 75 | 31 |
| 14 | [62%] | 75 | 31 |
| 15 | [62%] | 75 | 31 |
| 16 | [62%] | 75 | 31 |
| 17 | [62%] | 75 | 31 |
| 18 | [78%] | 102 | 57 |
| 19 | [85%] | 109 | 67 |
| 20 | [62%] | 81 | 33 |
| 21 | [62%] | 80 | 33 |
| 22 | [62%] | 75 | 31 |
| 23 | [62%] | 79 | 33 |
| 24 | [62%] | 77 | 32 |
| **Hour** | **Part Load** | **P_MT** | **H_MT** |
| 19 | [73%] | 37 | 87 |
| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
| 11 | [75%] | 113 | 215 |
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 153 | 252 |
| 14 | [100%] | 159 | 261 |
| 15 | [100%] | 164 | 269 |
| 16 | [100%] | 162 | 267 |
| 17 | [100%] | 154 | 253 |
| 18 | [50%] | 76 | 174 |

### E.7.11 *Hourly LCA Optimization Model* for min PE in a day in November

**Table 6-93: Supply from the energy systems in an average day in November (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 46 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 61 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 75 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 83 | 0 | 0 | 0 | 0 | 3 | 0 |
| 5 | 0 | 90 | 0 | 0 | 0 | 0 | 6 | 0 |
| 6 | 0 | 97 | 0 | 0 | 0 | 0 | 9 | 0 |
| 7 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 26 |
| 9 | 53 | 0 | 0 | 0 | 12 | 11 | 0 | 127 |
| 10 | 52 | 0 | 0 | 0 | 40 | 38 | 0 | 154 |
| 11 | 52 | 0 | 0 | 0 | 67 | 63 | 0 | 151 |
| 12 | 53 | 0 | 0 | 0 | 106 | 101 | 0 | 118 |
| 13 | 53 | 0 | 0 | 0 | 137 | 131 | 0 | 89 |
| 14 | 54 | 0 | 0 | 0 | 157 | 149 | 0 | 74 |
| 15 | 54 | 0 | 0 | 0 | 168 | 160 | 0 | 54 |
| 16 | 53 | 0 | 0 | 0 | 141 | 134 | 0 | 68 |
| 17 | 52 | 0 | 0 | 0 | 76 | 73 | 0 | 111 |
| 18 | 17 | 0 | 0 | 0 | 16 | 15 | 0 | 150 |
| 19 | 52 | 0 | 0 | 0 | 2 | 2 | 0 | 11 |
| 20 | 31 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 15 |
| 22 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 19 | [100%] | 48 | 96 |
| 20 | [100%] | 55 | 109 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 76 | 174 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |
| 8 | [100%] | 151 | 248 |
| 9 | [100%] | 151 | 248 |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 151 | 248 |

| Table 6-93 (continued) | | | |
|---|---|---|---|
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 151 | 248 |
| 15 | [100%] | 151 | 248 |
| 16 | [100%] | 151 | 248 |
| 17 | [100%] | 151 | 248 |
| 18 | [100%] | 151 | 248 |
| 21 | [50%] | 76 | 174 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 88 | 201 |
| 24 | [50%] | 85 | 194 |

### E.7.12 *Hourly LCA Optimization Model* for min PE in a day in December

**Table 6-94: Supply from the energy systems in an average day in December (Hourly model: min PE).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 178 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 194 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 210 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 223 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 235 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 244 | 0 | 0 | 0 | 0 | 2 | 0 |
| 7 | 0 | 217 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 172 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 41 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 61 | 0 | 0 | 0 | 5 | 4 | 0 | 57 |
| 11 | 60 | 0 | 0 | 0 | 15 | 15 | 0 | 105 |
| 12 | 60 | 0 | 0 | 0 | 29 | 28 | 0 | 121 |
| 13 | 60 | 0 | 0 | 0 | 57 | 55 | 0 | 104 |
| 14 | 61 | 0 | 0 | 0 | 78 | 75 | 0 | 92 |
| 15 | 62 | 0 | 0 | 0 | 81 | 77 | 0 | 92 |
| 16 | 61 | 0 | 0 | 0 | 52 | 49 | 0 | 105 |
| 17 | 60 | 0 | 0 | 0 | 16 | 15 | 0 | 92 |
| 18 | 24 | 0 | 0 | 0 | 6 | 6 | 0 | 42 |
| 19 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 17 |
| 20 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 133 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 139 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_MT | H_MT |
|---|---|---|---|
| 19 | [100%] | 48 | 96 |
| 20 | [100%] | 55 | 109 |

Table 6-94 (continued)

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 77 | 176 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [100%] | 158 | 259 |
| 9 | [100%] | 172 | 282 |
| 10 | [100%] | 151 | 248 |
| 11 | [100%] | 151 | 248 |
| 12 | [100%] | 151 | 248 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 151 | 248 |
| 15 | [100%] | 151 | 248 |
| 16 | [100%] | 151 | 248 |
| 17 | [100%] | 151 | 248 |
| 18 | [100%] | 151 | 248 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 94 | 215 |
| 21 | [50%] | 92 | 210 |
| 22 | [50%] | 90 | 205 |
| 23 | [50%] | 94 | 215 |
| 24 | [50%] | 91 | 208 |

## E.8 AVERAGE ELECTRIC OPTION: MIN COST

### E.8.1 *Hourly LCA Optimization Model* for min cost in a day in January

**Table 6-95: Supply from the energy systems in an average day in January (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 242 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 259 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 273 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 289 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 306 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 321 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 286 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6-95 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 8 | 0 | 145 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 42 | 53 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 97 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 11 | 135 | 0 | 0 | 0 | 9 | 8 | 0 | 22 |
| 12 | 216 | 113 | 5 | 22 | 0 | 0 | 0 | 0 |
| 13 | 219 | 95 | 8 | 35 | 0 | 0 | 0 | 0 |
| 14 | 223 | 82 | 12 | 54 | 0 | 0 | 0 | 0 |
| 15 | 226 | 89 | 15 | 70 | 0 | 0 | 0 | 0 |
| 16 | 137 | 0 | 1 | 3 | 60 | 58 | 0 | 0 |
| 17 | 140 | 0 | 4 | 20 | 8 | 8 | 0 | 0 |
| 18 | 19 | 0 | 0 | 2 | 0 | 0 | 0 | 0 |
| 19 | 0 | 52 | 0 | 0 | 0 | 0 | 3 | 0 |
| 20 | 0 | 110 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 1 | 209 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 231 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Hour** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 92 | 210 |
| 2 | [50%] | 89 | 203 |
| 3 | [50%] | 87 | 199 |
| 4 | [50%] | 84 | 192 |
| 5 | [50%] | 81 | 185 |
| 6 | [50%] | 78 | 178 |
| 7 | [50%] | 88 | 201 |
| 8 | [50%] | 80 (unit 1)<br>80 (unit 2) | 183 (unit 1)<br>183 (unit 2) |
| 9 | [100%] | 172 | 282 |
| 10 | [75%] | 115 | 218 |
| 11 | [50%] | 76 | 174 |
| 16 | [50%] | 76 | 174 |
| 17 | [50%] | 76 | 174 |
| 18 | [100%] | 158 | 260 |
| 19 | [75%] | 113 | 215 |
| 20 | [50%] | 97 | 221 |
| 21 | [50%] | 95 | 217 |
| 22 | [50%] | 93 | 212 |
| 23 | [50%] | 97 | 221 |
| 24 | [50%] | 95 | 217 |

### E.8.2 *Hourly LCA Optimization Model* for min cost in a day in February

**Table 6-96: Supply from the energy systems in an average day in February (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 177 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 196 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 214 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 232 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 248 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 263 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 229 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 136 | 0 | 0 | 0 | 21 | 20 | 0 | 18 |
| 11 | 221 | 94 | 9 | 41 | 0 | 0 | 0 | 0 |
| 12 | 226 | 68 | 14 | 64 | 0 | 0 | 0 | 0 |
| 13 | 231 | 49 | 19 | 86 | 0 | 0 | 0 | 0 |
| 14 | 233 | 47 | 21 | 97 | 0 | 0 | 0 | 0 |
| 15 | 238 | 52 | 26 | 121 | 0 | 0 | 0 | 0 |
| 16 | 238 | 67 | 26 | 120 | 0 | 0 | 0 | 0 |
| 17 | 233 | 82 | 21 | 97 | 0 | 0 | 0 | 0 |
| 18 | 100 | 0 | 0 | 0 | 27 | 26 | 0 | 21 |
| 19 | 29 | 0 | 0 | 0 | 1 | 1 | 0 | 30 |
| 20 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 39 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 95 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 118 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 127 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 78 | 178 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 79 (unit 1)<br>79 (unit 2) | 179 (unit 1)<br>179 (unit 2) |
| 9 | [75%] | 122 | 232 |
| 10 | [50%] | 76 | 174 |
| 18 | [50%] | 76 | 174 |
| 19 | [50%] | 76 | 174 |
| 20 | [50%] | 84 | 191 |
| 21 | [50%] | 89 | 203 |
| 22 | [50%] | 88 | 201 |

| Table 6-96 (continued) | | | |
|---|---|---|---|
| 23 | [50%] | 93 | 212 |
| 24 | [50%] | 91 | 208 |

### E.8.3 *Hourly LCA Optimization Model* for min cost in a day in March

**Table 6-97: Supply from the energy systems in an average day in March (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 54 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 74 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 92 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 109 | 0 | 0 | 0 | 0 | 2 | 0 |
| 5 | 0 | 118 | 0 | 0 | 0 | 0 | 5 | 0 |
| 6 | 0 | 127 | 0 | 0 | 0 | 0 | 8 | 0 |
| 7 | 0 | 99 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 3 | 0 | 0 | 0 | 1 | 1 | 0 | 8 |
| 9 | 135 | 0 | 0 | 0 | 35 | 33 | 0 | 14 |
| 10 | 231 | 81 | 19 | 86 | 0 | 0 | 0 | 0 |
| 11 | 242 | 58 | 29 | 131 | 0 | 0 | 0 | 0 |
| 12 | 248 | 49 | 34 | 156 | 0 | 0 | 0 | 0 |
| 13 | 253 | 39 | 39 | 178 | 0 | 0 | 0 | 0 |
| 14 | 261 | 36 | 46 | 209 | 0 | 0 | 0 | 0 |
| 15 | 263 | 38 | 48 | 222 | 0 | 0 | 0 | 0 |
| 16 | 264 | 44 | 49 | 224 | 0 | 0 | 0 | 0 |
| 17 | 253 | 55 | 39 | 180 | 0 | 0 | 0 | 0 |
| 18 | 198 | 73 | 22 | 102 | 0 | 0 | 0 | 0 |
| 19 | 109 | 68 | 5 | 25 | 0 | 0 | 0 | 0 |
| 20 | 89 | 97 | 2 | 8 | 0 | 0 | 0 | 0 |
| 21 | 9 | 0 | 0 | 0 | 3 | 3 | 0 | 36 |
| 22 | 5 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 23 | 0 | 7 | 0 | 1 | 0 | 0 | 0 | 0 |
| 24 | 0 | 29 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 77 | 176 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 77 | 176 |
| 8 | [100%] | 151 | 248 |
| 9 | [50%] | 76 | 174 |
| 21 | [50%] | 76 | 174 |

| Table 6-97 (continued) | | | |
|---|---|---|---|
| 22 | [50%] | 78 | 179 |
| 23 | [50%] | 87 | 199 |
| 24 | [50%] | 85 | 194 |

### E.8.4 *Hourly LCA Optimization Model* for min cost in a day in April

**Table 6-98: Supply from the energy systems in an average day in April (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 74 | 53 | 0 | 0 | 0 | 0 |
| 2 | 71 | 64 | 0 | 0 | 0 | 0 |
| 3 | 68 | 81 | 0 | 0 | 0 | 0 |
| 4 | 66 | 96 | 0 | 0 | 0 | 0 |
| 5 | 63 | 112 | 0 | 0 | 0 | 0 |
| 6 | 60 | 129 | 0 | 0 | 0 | 0 |
| 7 | 71 | 109 | 0 | 0 | 0 | 0 |
| 8 | 160 | 81 | 0 | 2 | 0 | 0 |
| 9 | 230 | 31 | 10 | 45 | 0 | 0 |
| 10 | 248 | 19 | 27 | 125 | 0 | 0 |
| 11 | 264 | 16 | 42 | 193 | 0 | 0 |
| 12 | 277 | 17 | 54 | 246 | 0 | 0 |
| 13 | 284 | 16 | 60 | 274 | 0 | 0 |
| 14 | 293 | 16 | 69 | 314 | 0 | 0 |
| 15 | 299 | 16 | 74 | 341 | 0 | 0 |
| 16 | 302 | 17 | 77 | 352 | 0 | 0 |
| 17 | 297 | 17 | 73 | 334 | 0 | 0 |
| 18 | 244 | 17 | 59 | 271 | 0 | 0 |
| 19 | 147 | 15 | 34 | 153 | 0 | 0 |
| 20 | 103 | 14 | 13 | 62 | 0 | 0 |
| 21 | 86 | 16 | 4 | 16 | 0 | 0 |
| 22 | 77 | 20 | 1 | 4 | 0 | 0 |
| 23 | 79 | 24 | 0 | 1 | 0 | 0 |
| 24 | 77 | 53 | 0 | 0 | 0 | 0 |

### E.8.5 *Hourly LCA Optimization Model* for min cost in a day in May

**Table 6-99: Supply from the energy systems in an average day in May (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 74 | 9 | 2 | 7 | 0 | 0 |
| 2 | 70 | 13 | 1 | 5 | 0 | 0 |
| 3 | 67 | 17 | 1 | 3 | 0 | 0 |
| 4 | 63 | 21 | 0 | 1 | 0 | 0 |

| Table 6-99 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 5 | 59 | 25 | 0 | 1 | 0 | 0 |
| 6 | 56 | 31 | 0 | 1 | 0 | 0 |
| 7 | 68 | 21 | 1 | 7 | 0 | 0 |
| 8 | 171 | 21 | 14 | 62 | 0 | 0 |
| 9 | 254 | 16 | 36 | 163 | 0 | 0 |
| 10 | 275 | 16 | 56 | 255 | 0 | 0 |
| 11 | 292 | 16 | 72 | 329 | 0 | 0 |
| 12 | 302 | 17 | 81 | 369 | 0 | 0 |
| 13 | 306 | 16 | 85 | 389 | 0 | 0 |
| 14 | 311 | 16 | 89 | 409 | 0 | 0 |
| 15 | 316 | 16 | 94 | 429 | 0 | 0 |
| 16 | 319 | 17 | 97 | 443 | 0 | 0 |
| 17 | 312 | 17 | 91 | 416 | 0 | 0 |
| 18 | 262 | 14 | 79 | 361 | 0 | 0 |
| 19 | 176 | 11 | 58 | 266 | 0 | 0 |
| 20 | 125 | 8 | 32 | 147 | 0 | 0 |
| 21 | 95 | 6 | 12 | 55 | 0 | 0 |
| 22 | 82 | 6 | 5 | 23 | 0 | 0 |
| 23 | 82 | 6 | 3 | 15 | 0 | 0 |
| 24 | 78 | 6 | 2 | 10 | 0 | 0 |

### E.8.6 *Hourly LCA Optimization Model* for min cost in a day in June

**Table 6-100: Supply from the energy systems in an average day in June (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 79 | 6 | 6 | 26 | 0 | 0 |
| 2 | 75 | 6 | 5 | 22 | 0 | 0 |
| 3 | 70 | 6 | 4 | 19 | 0 | 0 |
| 4 | 66 | 6 | 3 | 15 | 0 | 0 |
| 5 | 61 | 7 | 2 | 11 | 0 | 0 |
| 6 | 58 | 8 | 2 | 9 | 0 | 0 |
| 7 | 78 | 6 | 10 | 44 | 0 | 0 |
| 8 | 193 | 16 | 40 | 184 | 0 | 0 |
| 9 | 277 | 15 | 66 | 304 | 0 | 0 |
| 10 | 299 | 15 | 86 | 395 | 0 | 0 |
| 11 | 317 | 15 | 103 | 470 | 0 | 0 |
| 12 | 326 | 17 | 111 | 507 | 0 | 0 |
| 13 | 328 | 15 | 113 | 517 | 0 | 0 |
| 14 | 332 | 15 | 117 | 536 | 0 | 0 |
| 15 | 335 | 15 | 120 | 548 | 0 | 0 |
| 16 | 341 | 17 | 125 | 574 | 0 | 0 |
| 17 | 339 | 17 | 123 | 563 | 0 | 0 |
| 18 | 287 | 13 | 108 | 495 | 0 | 0 |

| Table 6-101 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 19 | 210 | 10 | 90 | 411 | 0 | 0 |
| 20 | 155 | 8 | 58 | 265 | 0 | 0 |
| 21 | 113 | 6 | 27 | 124 | 0 | 0 |
| 22 | 93 | 6 | 14 | 64 | 0 | 0 |
| 23 | 91 | 6 | 10 | 44 | 0 | 0 |
| 24 | 84 | 6 | 7 | 34 | 0 | 0 |

### E.8.7 *Hourly LCA Optimization Model* for min cost in a day in July

**Table 6-101: Supply from the energy systems in an average day in July (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 88 | 6 | 13 | 60 | 0 | 0 |
| 2 | 82 | 6 | 11 | 52 | 0 | 0 |
| 3 | 78 | 6 | 10 | 45 | 0 | 0 |
| 4 | 72 | 6 | 8 | 38 | 0 | 0 |
| 5 | 67 | 6 | 7 | 31 | 0 | 0 |
| 6 | 63 | 6 | 6 | 27 | 0 | 0 |
| 7 | 83 | 6 | 14 | 64 | 0 | 0 |
| 8 | 210 | 17 | 51 | 236 | 0 | 0 |
| 9 | 301 | 16 | 81 | 372 | 0 | 0 |
| 10 | 326 | 16 | 105 | 483 | 0 | 0 |
| 11 | 349 | 16 | 126 | 575 | 0 | 0 |
| 12 | 364 | 17 | 141 | 648 | 0 | 0 |
| 13 | 372 | 16 | 149 | 683 | 0 | 0 |
| 14 | 375 | 16 | 152 | 698 | 0 | 0 |
| 15 | 382 | 16 | 159 | 729 | 0 | 0 |
| 16 | 390 | 17 | 166 | 762 | 0 | 0 |
| 17 | 389 | 17 | 165 | 756 | 0 | 0 |
| 18 | 331 | 14 | 145 | 664 | 0 | 0 |
| 19 | 249 | 11 | 121 | 552 | 0 | 0 |
| 20 | 180 | 8 | 78 | 358 | 0 | 0 |
| 21 | 132 | 6 | 42 | 192 | 0 | 0 |
| 22 | 108 | 6 | 26 | 119 | 0 | 0 |
| 23 | 103 | 6 | 20 | 91 | 0 | 0 |
| 24 | 95 | 6 | 16 | 74 | 0 | 0 |

### E.8.8 *Hourly LCA Optimization Model* for min cost in a day in August

**Table 6-102: Supply from the energy systems in an average day in August (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 85 | 6 | 11 | 49 | 0 | 0 |
| 2 | 80 | 6 | 9 | 40 | 0 | 0 |
| 3 | 74 | 6 | 7 | 34 | 0 | 0 |
| 4 | 70 | 6 | 6 | 29 | 0 | 0 |
| 5 | 65 | 6 | 5 | 25 | 0 | 0 |
| 6 | 62 | 6 | 5 | 22 | 0 | 0 |
| 7 | 75 | 6 | 7 | 33 | 0 | 0 |
| 8 | 199 | 17 | 41 | 189 | 0 | 0 |
| 9 | 295 | 16 | 75 | 343 | 0 | 0 |
| 10 | 322 | 16 | 100 | 459 | 0 | 0 |
| 11 | 347 | 16 | 124 | 567 | 0 | 0 |
| 12 | 361 | 17 | 137 | 626 | 0 | 0 |
| 13 | 366 | 16 | 142 | 652 | 0 | 0 |
| 14 | 370 | 16 | 147 | 674 | 0 | 0 |
| 15 | 377 | 16 | 153 | 703 | 0 | 0 |
| 16 | 383 | 17 | 159 | 727 | 0 | 0 |
| 17 | 378 | 17 | 154 | 707 | 0 | 0 |
| 18 | 313 | 14 | 128 | 588 | 0 | 0 |
| 19 | 223 | 11 | 99 | 452 | 0 | 0 |
| 20 | 152 | 8 | 55 | 254 | 0 | 0 |
| 21 | 116 | 6 | 29 | 132 | 0 | 0 |
| 22 | 98 | 6 | 18 | 84 | 0 | 0 |
| 23 | 96 | 6 | 14 | 65 | 0 | 0 |
| 24 | 90 | 6 | 12 | 55 | 0 | 0 |

### E.8.9 *Hourly LCA Optimization Model* for min cost in a day in September

**Table 6-103: Supply from the energy systems in an average day in September (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 76 | 6 | 3 | 16 | 0 | 0 |
| 2 | 72 | 6 | 3 | 12 | 0 | 0 |
| 3 | 68 | 7 | 2 | 10 | 0 | 0 |
| 4 | 65 | 9 | 2 | 7 | 0 | 0 |
| 5 | 60 | 12 | 1 | 6 | 0 | 0 |
| 6 | 57 | 15 | 1 | 4 | 0 | 0 |

| Table 6-103 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 7 | 68 | 18 | 2 | 8 | 0 | 0 |
| 8 | 169 | 19 | 17 | 79 | 0 | 0 |
| 9 | 248 | 15 | 38 | 173 | 0 | 0 |
| 10 | 275 | 15 | 62 | 284 | 0 | 0 |
| 11 | 297 | 15 | 83 | 379 | 0 | 0 |
| 12 | 309 | 17 | 94 | 430 | 0 | 0 |
| 13 | 318 | 15 | 102 | 468 | 0 | 0 |
| 14 | 324 | 15 | 108 | 493 | 0 | 0 |
| 15 | 330 | 15 | 114 | 523 | 0 | 0 |
| 16 | 334 | 17 | 118 | 541 | 0 | 0 |
| 17 | 326 | 17 | 110 | 504 | 0 | 0 |
| 18 | 263 | 13 | 85 | 389 | 0 | 0 |
| 19 | 170 | 10 | 56 | 257 | 0 | 0 |
| 20 | 117 | 8 | 27 | 122 | 0 | 0 |
| 21 | 97 | 6 | 14 | 65 | 0 | 0 |
| 22 | 85 | 6 | 8 | 36 | 0 | 0 |
| 23 | 86 | 6 | 6 | 25 | 0 | 0 |
| 24 | 80 | 6 | 4 | 20 | 0 | 0 |

### E.8.10 *Hourly LCA Optimization Model* for min cost in a day in October

**Table 6-104: Supply from the energy systems in an average day in October (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC |
|---|---|---|---|---|---|---|
| 1 | 74 | 55 | 0 | 0 | 0 | 0 |
| 2 | 71 | 68 | 0 | 0 | 0 | 0 |
| 3 | 68 | 83 | 0 | 0 | 0 | 0 |
| 4 | 66 | 96 | 0 | 0 | 0 | 0 |
| 5 | 63 | 110 | 0 | 0 | 0 | 0 |
| 6 | 60 | 123 | 0 | 0 | 0 | 0 |
| 7 | 71 | 125 | 0 | 0 | 0 | 0 |
| 8 | 157 | 111 | 1 | 3 | 0 | 0 |
| 9 | 220 | 29 | 5 | 24 | 0 | 0 |
| 10 | 239 | 16 | 23 | 107 | 0 | 0 |
| 11 | 262 | 16 | 45 | 208 | 0 | 0 |
| 12 | 280 | 17 | 61 | 280 | 0 | 0 |
| 13 | 289 | 16 | 70 | 321 | 0 | 0 |
| 14 | 297 | 16 | 77 | 351 | 0 | 0 |
| 15 | 303 | 16 | 82 | 376 | 0 | 0 |
| 16 | 301 | 17 | 81 | 372 | 0 | 0 |
| 17 | 290 | 17 | 71 | 324 | 0 | 0 |
| 18 | 230 | 14 | 49 | 224 | 0 | 0 |
| 19 | 122 | 11 | 15 | 70 | 0 | 0 |
| 20 | 89 | 8 | 4 | 16 | 0 | 0 |

| Table 6-104 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 21 | 81 | 7 | 1 | 4 | 0 | 0 |
| 22 | 75 | 14 | 0 | 1 | 0 | 0 |
| 23 | 79 | 29 | 0 | 0 | 0 | 0 |
| 24 | 77 | 44 | 0 | 0 | 0 | 0 |

### E.8.11 *Hourly LCA Optimization Model* for min cost in a day in November

**Table 6-105: Supply from the energy systems in an average day in November (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 46 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 61 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 75 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 83 | 0 | 0 | 0 | 0 | 3 | 0 |
| 5 | 0 | 90 | 0 | 0 | 0 | 0 | 6 | 0 |
| 6 | 0 | 97 | 0 | 0 | 0 | 0 | 9 | 0 |
| 7 | 0 | 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 207 | 110 | 3 | 12 | 0 | 0 | 0 | 0 |
| 10 | 212 | 56 | 9 | 40 | 0 | 0 | 0 | 0 |
| 11 | 218 | 34 | 15 | 67 | 0 | 0 | 0 | 0 |
| 12 | 227 | 29 | 23 | 106 | 0 | 0 | 0 | 0 |
| 13 | 234 | 28 | 30 | 137 | 0 | 0 | 0 | 0 |
| 14 | 239 | 25 | 34 | 157 | 0 | 0 | 0 | 0 |
| 15 | 242 | 34 | 37 | 168 | 0 | 0 | 0 | 0 |
| 16 | 235 | 46 | 31 | 141 | 0 | 0 | 0 | 0 |
| 17 | 220 | 64 | 17 | 76 | 0 | 0 | 0 | 0 |
| 18 | 171 | 83 | 3 | 16 | 0 | 0 | 0 | 0 |
| 19 | 100 | 82 | 0 | 2 | 0 | 0 | 0 | 0 |
| 20 | 86 | 119 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 15 |
| 22 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 21 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 43 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 82 | 187 |
| 2 | [50%] | 79 | 180 |
| 3 | [50%] | 76 | 174 |
| 4 | [50%] | 76 | 174 |
| 5 | [50%] | 76 | 174 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 76 | 174 |
| 8 | [75%] | 117 | 222 |

| Table 6-105 (continued) | | | |
|---|---|---|---|
| 21 | [50%] | 76 | 174 |
| 22 | [50%] | 83 | 189 |
| 23 | [50%] | 88 | 201 |
| 24 | [50%] | 85 | 194 |

### E.8.12 *Hourly LCA Optimization Model* for min cost in a day in December

**Table 6-106: Supply from the energy systems in an average day in December (Hourly model: min cost).**

| Hour | P_GRID | H_BOILER | P_EC | C_EC | C_AC | H_AC | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 178 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 194 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 210 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 223 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 235 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 244 | 0 | 0 | 0 | 0 | 2 | 0 |
| 7 | 0 | 217 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 70 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 41 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 132 | 0 | 1 | 5 | 0 | 0 | 0 | 0 |
| 11 | 135 | 0 | 0 | 0 | 15 | 15 | 0 | 31 |
| 12 | 217 | 99 | 6 | 29 | 0 | 0 | 0 | 0 |
| 13 | 224 | 89 | 13 | 57 | 0 | 0 | 0 | 0 |
| 14 | 229 | 81 | 17 | 78 | 0 | 0 | 0 | 0 |
| 15 | 231 | 79 | 18 | 81 | 0 | 0 | 0 | 0 |
| 16 | 223 | 93 | 11 | 52 | 0 | 0 | 0 | 0 |
| 17 | 135 | 0 | 0 | 0 | 16 | 15 | 0 | 18 |
| 18 | 62 | 0 | 0 | 0 | 6 | 6 | 0 | 9 |
| 19 | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 133 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 139 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 156 | 0 | 0 | 0 | 0 | 0 | 0 |

| Hour | Part Load | P_ICE | H_ICE |
|---|---|---|---|
| 1 | [50%] | 89 | 203 |
| 2 | [50%] | 86 | 196 |
| 3 | [50%] | 83 | 189 |
| 4 | [50%] | 80 | 183 |
| 5 | [50%] | 77 | 176 |
| 6 | [50%] | 76 | 174 |
| 7 | [50%] | 84 | 192 |
| 8 | [50%] | 82 (unit 1)<br>82 (unit 2) | 187 (unit 1)<br>187 (unit 2) |

| Table 6-106 (continued) | | | |
|---|---|---|---|
| 9 | [100%] | 172 | 282 |
| 10 | [50%] | 81 | 186 |
| 11 | [50%] | 76 | 174 |
| 17 | [50%] | 76 | 174 |
| 18 | [75%] | 113 | 215 |
| 19 | [50%] | 87 | 198 |
| 20 | [50%] | 94 | 215 |
| 21 | [50%] | 92 | 210 |
| 22 | [50%] | 90 | 205 |
| 23 | [50%] | 94 | 215 |
| 24 | [50%] | 91 | 208 |

## E.9 AVERAGE ELECTRIC OPTION (YEARLY MODEL)

### E.9.1 *Simplified yearly LCA Optimization Model* for min GWP in a year

**Table 6-107: Supply from the energy systems in a year (Yearly model: min GWP).**

| Period | P_Grid | H_Boiler | P_E | C_E | C_A | H_A | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 241 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 81 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 47 | 45 | 0 | 195 |
| 4 | 4 | 0 | 0 | 0 | 12 | 11 | 0 | 75 |
| 5 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 89 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 |
| 8 | 37 | 0 | 0 | 0 | 129 | 123 | 0 | 107 |
| 9 | 0 | 0 | 0 | 0 | 59 | 56 | 0 | 148 |
| 10 | 0 | 0 | 0 | 0 | 3 | 3 | 0 | 38 |
| 11 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 16 |
| 12 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 162 |
| 13 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 119 |
| 14 | 11 | 0 | 0 | 0 | 248 | 236 | 0 | 30 |
| 15 | 30 | 0 | 0 | 0 | 27 | 26 | 0 | 63 |
| 16 | 10 | 0 | 0 | 0 | 4 | 4 | 0 | 86 |
| 17 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 178 |
| 18 | 0 | 0 | 0 | 0 | 356 | 339 | 0 | 25 |
| 19 | 0 | 0 | 6 | 26 | 335 | 319 | 0 | 0 |
| 20 | 33 | 0 | 0 | 0 | 86 | 82 | 0 | 20 |
| 21 | 10 | 0 | 0 | 0 | 15 | 14 | 0 | 87 |
| 22 | 0 | 0 | 0 | 0 | 131 | 125 | 0 | 109 |

Table 6-107 (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 23 | 2 | 0 | 13 | 61 | 395 | 376 | 0 | 0 |
| 24 | 0 | 0 | 20 | 90 | 352 | 335 | 0 | 0 |
| 25 | 0 | 0 | 0 | 0 | 122 | 116 | 0 | 78 |
| 26 | 11 | 0 | 0 | 0 | 39 | 37 | 0 | 66 |
| 27 | 0 | 0 | 0 | 0 | 213 | 203 | 0 | 41 |
| 28 | 0 | 0 | 31 | 143 | 477 | 454 | 0 | 0 |
| 29 | 0 | 0 | 43 | 197 | 429 | 409 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 202 | 192 | 0 | 13 |

| **Period** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 3 | [100%] | 48 | 96 |
| 11 | [100%] | 55 | 109 |
| 13 | [100%] | 49 | 98 |
| 15 | [100%] | 55 | 109 |
| 16 | [100%] | 55 | 109 |
| 18 | [100%] | 49 | 98 |
| 19 | [75%] | 34 | 79 |
| 20 | [100%] | 55 | 109 |
| 21 | [100%] | 55 | 109 |
| 23 | [100%] | 55 | 109 |
| 24 | [75%] | 34 | 79 |
| 26 | [100%] | 55 | 109 |

| **Period** | **Part Load** | **P_ICE** | **H_ICE** |
|---|---|---|---|
| 1 | [50%] | 83 | 189 |
| 2 | [50%] | 79 (unit 1)<br>79 (unit 2) | 180 (unit 1)<br>180 (unit 2) |
| 3 | [100%] | 164 | 269 |
| 4 | [100%] | 172 | 282 |
| 5 | [50%] | 95 | 217 |
| 6 | [50%] | 76 | 174 |
| 7 | [100%] | 152 | 250 |
| 8 | [100%] | 172 | 282 |
| 9 | [100%] | 172 | 282 |
| 10 | [50%] | 88 | 201 |
| 12 | [100%] | 158 | 259 |
| 13 | [100%] | 172 | 282 |
| 14 | [100%] | 172 | 282 |
| 17 | [100%] | 157 | 258 |
| 18 | [100%] | 172 | 282 |
| 19 | [100%] | 155 | 254 |
| 22 | [100%] | 153 | 251 |
| 23 | [100%] | 172 | 282 |
| 24 | [100%] | 164 | 269 |
| 25 | [50%] | 88 | 201 |
| 27 | [100%] | 159 | 261 |
| 28 | [100%], [50%] | 172 [100%] (unit 1)<br>82 [50%] (unit 2) | 282 [100%]<br>188 [50%] |

| Table 6-107 (continued) | | | |
|---|---|---|---|
| 29 | [100%], [50%] | 152 [100%] (unit 1)<br>76 [50%] (unit 2) | 249[100%]<br>174 [50%] |
| 30 | [50%] | 93 | 212 |

### E.9.2 Simplified yearly LCA Optimization Model for min AP in a year

**Table 6-108: Supply from the energy systems in a year (Yearly model: min AP).**

| Period | P_Grid | H_Boiler | P_E | C_E | C_A | H_A | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 163 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 93 | 0 |
| 3 | 0 | 0 | 0 | 0 | 47 | 45 | 0 | 99 |
| 4 | 0 | 0 | 1 | 4 | 8 | 8 | 0 | 0 |
| 5 | 0 | 3 | 0 | 0 | 0 | 0 | 99 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 95 | 0 |
| 7 | 0 | 14 | 0 | 0 | 0 | 0 | 2 | 0 |
| 8 | 0 | 0 | 0 | 0 | 129 | 123 | 0 | 88 |
| 9 | 0 | 0 | 0 | 0 | 59 | 56 | 0 | 49 |
| 10 | 0 | 36 | 1 | 3 | 0 | 0 | 26 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 29 | 0 |
| 12 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 65 |
| 13 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 20 |
| 14 | 0 | 0 | 3 | 15 | 233 | 221 | 0 | 0 |
| 15 | 0 | 0 | 1 | 6 | 21 | 20 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 4 | 4 | 10 | 7 |
| 17 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 82 |
| 18 | 0 | 0 | 10 | 47 | 309 | 295 | 0 | 0 |
| 19 | 0 | 0 | 23 | 104 | 257 | 245 | 0 | 0 |
| 20 | 0 | 0 | 8 | 37 | 49 | 47 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 15 | 14 | 10 | 8 |
| 22 | 0 | 0 | 0 | 0 | 131 | 125 | 0 | 17 |
| 23 | 0 | 0 | 26 | 118 | 338 | 322 | 0 | 0 |
| 24 | 0 | 0 | 37 | 171 | 271 | 258 | 0 | 0 |
| 25 | 0 | 0 | 14 | 64 | 58 | 55 | 0 | 0 |
| 26 | 0 | 0 | 9 | 39 | 0 | 0 | 0 | 25 |
| 27 | 0 | 0 | 10 | 45 | 168 | 160 | 0 | 0 |
| 28 | 0 | 0 | 51 | 232 | 388 | 370 | 0 | 0 |
| 29 | 0 | 0 | 60 | 276 | 350 | 333 | 0 | 0 |
| 30 | 0 | 0 | 27 | 125 | 77 | 73 | 0 | 0 |

| **Period** | **Part Load** | **P_FC** | **H_FC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |

| Table 6-108 (continued) | | | |
|---|---|---|---|
| 3 | [93%] | 116 | 77 |
| 4 | [104%] | 129 | 108 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [62%] | 75 | 31 |
| 11 | [62%] | 75 | 31 |
| 12 | [85%] | 110 | 67 |
| 13 | [93%] | 119 | 80 |
| 14 | [93%] | 119 | 79 |
| 15 | [68%] | 86 | 41 |
| 16 | [62%] | 75 | 31 |
| 17 | [85%] | 109 | 67 |
| 18 | [104%] | 130 | 109 |
| 19 | [85%] | 110 | 67 |
| 20 | [78%] | 96 | 54 |
| 21 | [62%] | 75 | 31 |
| 22 | [93%] | 119 | 79 |
| 23 | [85%] | 111 | 68 |
| 24 | [93%] | 119 | 80 |
| 25 | [85%] | 102 | 63 |
| 26 | [62%] | 75 | 31 |
| 27 | [93%] | 120 | 80 |
| 28 | [93%] | 120 | 80 |
| 29 | [62%] | 0 | 0 |
| 30 | [93%] | 120 | 80 |

**P_MT**

| Period | Part Load | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1 | [75%] | 34 | 34 | 34 | 34 | 34 |
| 2 | [75%] | 36 | 36 | 36 | 34 | 34 |
| 3 | [100%] | 48 | 48 | | | |
| 4 | [100%] | 48 | 0 | | | |
| 5 | [75%] | 40 | 40 | 40 | | |
| 6 | [75%], [50%] | 37 | 37 | 21 [50%] | | |
| 7 | [75%] | 40 | 40 | | | |
| 8 | [100%] | 50 | 48 | | | |
| 9 | [100%] | 52 | 0 | | | |
| 10 | [75%] | 40 | 0 | | | |
| 11 | [50%] | 22 | 0 | | | |
| 12 | [100%] | 48 | 0 | | | |
| 13 | [100%] | 53 | 48 | | | |
| 14 | [75%] | 34 | 34 | | | |
| 17 | [100%] | 48 | 0 | | | |
| 18 | [100%] | 51 | 51 | | | |

| Table 6-108 (continued) | | | | | | |
|---|---|---|---|---|---|---|
| 19 | [100%] | 48 | 48 | | | |
| 22 | [75%] | 34 | 0 | | | |
| 23 | [100%], [75%] | 48 [100%] | 48 [100%] | 34 [75%] | | |
| 24 | [100%] | 48 | 48 | | | |
| 27 | [100%] | 48 | 0 | | | |
| 28 | [100%] | 55 | 49 | | | |
| 29 | [100%], [75%] | 50 [100%] | 50 [100%] | 34 [75%] | | |
| | | | **H_MT** | | | |
| Period | Part Load | 1 | 2 | 3 | 4 | 5 |
| 1 | [75%] | 80 | 80 | 80 | 80 | 80 |
| 2 | [75%] | 84 | 84 | 84 | 79 | 79 |
| 3 | [100%] | 96 | 96 | 0 | | |
| 4 | [100%] | 96 | 0 | 0 | | |
| 5 | [75%] | 93 | 93 | 93 | | |
| 6 | [75%], [50%] | 87 [75%] | 87 [75%] | 58 [50%] | | |
| 7 | [75%] | 93 | 93 | 0 | | |
| 8 | [100%] | 100 | 96 | 0 | | |
| 9 | [100%] | 103 | 0 | 0 | | |
| 11 | [50%] | 62 | 0 | 0 | | |
| 12 | [100%] | 96 | 0 | 0 | | |
| 13 | [100%] | 105 | 96 | 0 | | |
| 14 | [75%] | 79 | 79 | 0 | | |
| 17 | [100%] | 96 | 0 | 0 | | |
| 18 | [100%] | 101 | 101 | 0 | | |
| 19 | [100%] | 96 | 96 | 0 | | |
| 22 | [75%] | 79 | 0 | 0 | | |
| 23 | [100%], [75%] | 96 [100%] | 96 [100%] | 79 [75%] | | |
| 24 | [100%] | 96 | 96 | 0 | | |
| 27 | [100%] | 97 | 0 | 0 | | |
| 28 | [100%] | 109 | 98 | 98 | | |
| 29 | [100%], [75%] | 100 [100%] | 100 [100%] | 79 [75%] | | |

## E.10 NGCC OPTION (YEARLY MODEL)

### E.10.1 Simplified yearly LCA Optimization Model for min GWP in a year (NGCC)

**Table 6-109: Supply from the energy systems in a year (Yearly model-NGCC: min GWP).**

| Period | P_NGCC | H_Boiler | P_E | C_E | C_A | H_A | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 241 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 81 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 136 | 0 | 0 | 0 | 47 | 45 | 0 | 4 |
| 4 | 63 | 0 | 0 | 0 | 12 | 11 | 0 | 7 |
| 5 | 0 | 96 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 89 | 0 | 0 | 0 | 0 | 1 | 0 |
| 7 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 17 |
| 8 | 197 | 0 | 22 | 101 | 28 | 26 | 0 | 0 |
| 9 | 151 | 0 | 13 | 58 | 1 | 1 | 0 | 0 |
| 10 | 12 | 0 | 0 | 0 | 3 | 3 | 0 | 11 |
| 11 | 28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 119 | 3 | 0 | 2 | 0 | 0 | 0 | 0 |
| 13 | 73 | 0 | 3 | 14 | 241 | 230 | 0 | 0 |
| 14 | 33 | 0 | 1 | 4 | 244 | 232 | 0 | 0 |
| 15 | 91 | 21 | 6 | 27 | 0 | 0 | 0 | 0 |
| 16 | 66 | 20 | 1 | 4 | 0 | 0 | 0 | 0 |
| 17 | 171 | 21 | 14 | 62 | 0 | 0 | 0 | 0 |
| 18 | 95 | 0 | 25 | 112 | 244 | 232 | 0 | 0 |
| 19 | 57 | 0 | 25 | 115 | 246 | 234 | 0 | 0 |
| 20 | 107 | 7 | 19 | 86 | 0 | 0 | 0 | 0 |
| 21 | 68 | 8 | 3 | 15 | 0 | 0 | 0 | 0 |
| 22 | 182 | 17 | 29 | 131 | 0 | 0 | 0 | 0 |
| 23 | 110 | 0 | 46 | 212 | 244 | 232 | 0 | 0 |
| 24 | 70 | 0 | 43 | 195 | 247 | 235 | 0 | 0 |
| 25 | 115 | 7 | 27 | 122 | 0 | 0 | 0 | 0 |
| 26 | 75 | 6 | 9 | 39 | 0 | 0 | 0 | 0 |
| 27 | 206 | 17 | 47 | 213 | 0 | 0 | 0 | 0 |
| 28 | 154 | 0 | 82 | 376 | 244 | 232 | 0 | 0 |
| 29 | 117 | 0 | 83 | 380 | 246 | 234 | 0 | 0 |
| 30 | 137 | 7 | 44 | 202 | 0 | 0 | 0 | 0 |

| **Period** | **Part Load** | **P_MT** | **H_MT** |
|---|---|---|---|
| 8 | [75%] | 34 | 79 |
| 9 | [75%] | 34 | 79 |
| 11 | [75%] | 40 | 93 |
| 12 | [75%] | 40 | 93 |
| P_ICE | | | |

| Table 6-109 (continued) | | | |
|---|---|---|---|
| Period | Part Load | P_ICE | H_ICE |
| 1 | [50%] | 83 | 189 |
| 2 | [50%] | 79 (unit 1)<br>79 (unit 2) | 180 (unit 1)<br>180 (unit 2) |
| 3 | | 76 | 174 |
| 4 | [75%] | 113 | 215 |
| 5 | [50%] | 95 | 217 |
| 6 | [50%] | 76 | 174 |
| 7 | [100%] | 151 | 248 |
| 10 | [50%] | 76 | 174 |
| 13 | [100%] | 151 | 248 |
| 14 | [100%] | 151 | 248 |
| 18 | [100%] | 151 | 248 |
| 19 | [100%] | 151 | 248 |
| 23 | [100%] | 151 | 248 |
| 24 | [100%] | 151 | 248 |
| 28 | [100%] | 151 | 248 |
| 29 | [100%] | 151 | 248 |

**Table 6-110: Supply from the energy systems in a year (Yearly model-NGCC: min AP).**

| Period | P_NGCC | H_Boiler | P_E | C_E | C_A | H_A | P_EXCESS | H_EXCESS |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 163 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 93 | 0 |
| 3 | 0 | 0 | 0 | 0 | 47 | 45 | 0 | 99 |
| 4 | 0 | 0 | 1 | 4 | 8 | 8 | 0 | 0 |
| 5 | 0 | 3 | 0 | 0 | 0 | 0 | 99 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 95 | 0 |
| 7 | 0 | 14 | 0 | 0 | 0 | 0 | 2 | 0 |
| 8 | 0 | 0 | 0 | 0 | 129 | 123 | 0 | 88 |
| 9 | 0 | 0 | 0 | 0 | 59 | 56 | 0 | 49 |
| 10 | 0 | 36 | 1 | 3 | 0 | 0 | 26 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 29 | 0 |
| 12 | 0 | 0 | 0 | 0 | 2 | 2 | 0 | 65 |
| 13 | 0 | 0 | 0 | 0 | 255 | 243 | 0 | 20 |
| 14 | 0 | 0 | 3 | 15 | 233 | 221 | 0 | 0 |
| 15 | 0 | 0 | 1 | 6 | 21 | 20 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 4 | 4 | 10 | 7 |
| 17 | 0 | 0 | 0 | 0 | 62 | 59 | 0 | 82 |
| 18 | 0 | 0 | 10 | 47 | 309 | 295 | 0 | 0 |
| 19 | 0 | 0 | 23 | 104 | 257 | 245 | 0 | 0 |
| 20 | 0 | 0 | 8 | 37 | 49 | 47 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 15 | 14 | 10 | 8 |
| 22 | 0 | 0 | 0 | 0 | 131 | 125 | 0 | 17 |
| 23 | 0 | 0 | 26 | 118 | 338 | 322 | 0 | 0 |

| Table 6-110 (continued) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 24 | 0 | 0 | 37 | 171 | 271 | 258 | 0 | 0 |
| 25 | 0 | 0 | 14 | 64 | 58 | 55 | 0 | 0 |
| 26 | 0 | 0 | 9 | 39 | 0 | 0 | 0 | 25 |
| 27 | 0 | 0 | 10 | 45 | 168 | 160 | 0 | 0 |
| 28 | 0 | 0 | 51 | 232 | 388 | 370 | 0 | 0 |
| 29 | 0 | 0 | 60 | 276 | 350 | 333 | 0 | 0 |
| 30 | 0 | 0 | 27 | 125 | 77 | 73 | 0 | 0 |

| **Period** | **Part Load** | **P_FC** | **H_FC** |
|---|---|---|---|
| 1 | [62%] | 75 | 31 |
| 2 | [62%] | 75 | 31 |
| 3 | [93%] | 116 | 77 |
| 4 | [104%] | 129 | 108 |
| 5 | [62%] | 75 | 31 |
| 6 | [62%] | 75 | 31 |
| 7 | [62%] | 75 | 31 |
| 8 | [85%] | 111 | 68 |
| 9 | [93%] | 120 | 80 |
| 10 | [62%] | 75 | 31 |
| 11 | [62%] | 75 | 31 |
| 12 | [85%] | 110 | 67 |
| 13 | [93%] | 120 | 80 |
| 14 | [93%] | 118 | 79 |
| 15 | [68%] | 86 | 41 |
| 16 | [62%] | 75 | 31 |
| 17 | [85%] | 109 | 67 |
| 18 | [104%] | 130 | 109 |
| 19 | [85%] | 110 | 67 |
| 20 | [78%] | 96 | 54 |
| 21 | [62%] | 75 | 31 |
| 22 | [93%] | 119 | 79 |
| 23 | [85%] | 111 | 68 |
| 24 | [93%] | 119 | 80 |
| 25 | [85%] | 102 | 63 |
| 26 | [62%] | 75 | 31 |
| 27 | [93%] | 120 | 80 |
| 28 | [93%] | 120 | 80 |
| 29 | [85%] | 111 | 68 |
| 30 | [93%] | 120 | 80 |

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