INTEGRATED GENERATION MANAGEMENT FOR MAXIMIZING RENEWABLE RESOURCE UTILIZATION

by

Haifeng Xu

B.S. Electronic and Information Engineering,

Zhejiang University, 2009

Submitted to the Graduate Faculty of

the Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2012

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Haifeng Xu

It was defended on

March 29th 2012

and approved by

Alex K. Jones, PhD, Associate Professor, Department of Electrical and Computer Engineering

Zhi-Hong Mao, PhD, Associate Professor, Department of Electrical and Computer Engineering

Yiran Chen, PhD, Assistant Professor, Department of Electrical and Computer Engineering

Melissa M Bilec, PhD, Assistant Professor, Department of Civil Engineering

Thesis Advisor: Alex K. Jones, PhD, Associate Professor, Department of Electrical and Computer Engineering

INTEGRATED GENERATION MANAGEMENT FOR MAXIMIZING RENEWABLE RESOURCE UTILIZATION

Haifeng Xu, M.S.

University of Pittsburgh, 2012

Two proposed methods to reduce the effective intermittency and improve the efficiency of wind power generation in the grid are spatial smoothing of wind generation and utilization of short term electrical storage to deal with lulls in production. In this thesis, based on a concept called integrated generation management (IGM), we explore the impact of spatial smoothing and the use of emerging plug-in hybrid electric vehicles (PHEVs) as a potential storage resource to the smart-grid. IGM combines nuclear, slow load-following coal, fast load-following natural gas, and renewable wind generation with an optimal control method to maximize the renewable generation and minimize the fossil generation. With the increasing penetration of PHEVs, the power grid is seeing new opportunities to make itself smarter than ever by utilizing those relatively large batteries. Based on current projections of PHEV market penetration and various wind generation scenarios, we demonstrate the potential for efficient wind integration at levels of approaching 30% of the average electrical load with utilization efficiency exceeding 65%. At lower levels of integration (e.g. 15%), efficiencies are possible exceeding 85%.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

I would first thank my advisor, Dr. Alex Jones. Without his relentless support, insightful instruction and advice, I could never have learned so much during this work. His attitude towards research steered me in the right direction for my past, current and future studies. I'm truly thankful to his allowing me the precious opportunity to purse my graduate study in the University of Pittsburgh.

I want to thank Dr. Zhi-Hong Mao for his co-advice on my research. Throughout my master study and research, his outstanding experience on research and positive attitude towards work always inspire me to the right way I should pursue. I also thank Professor Yiran Che and Professor Melissa Bilec for joining my committee and giving me precious advice on my thesis. I further thank my fellow researcher, Iheanyi Umez-Eronini for his help to accelerate my research.

Finally, I thank my parents for their regardless care and support.

1.0 INTRODUCTION

Renewable energy is the fastest-growing form of electricity generation and is projected to supply an increasing share of the world's total electricity demand. Despite positive environmental and energy security properties, most renewable technologies cannot compete practically with fossil fuels because of current high production cost and low utilization. Utilization of renewable power generation has been limited due to several factors. Renewable power sources such as solar and wind are intermittent creating reliability problems. Additionally, generation sources are typically geographically distant from the places where the power is to be heavily used. This is typically because heavy availability of the resource is not desirable for population centers and photo-voltaic cells and turbines for collecting solar and wind energy are considered "unsightly" and are resisted near population centers. These factors have resulted in very small amounts of renewable generation from penetrating our grid.

Our motivation to improve renewable resource utilization comes with its increasing contribution to US electricity power production. An estimate of 20% wind energy penetration will be achieved by the year 2030 [1]. However, with the rapid expanding of the production capacity, a major difficulty that becomes more significant with utilizing wind as a stable supply to the power grid is the unstable nature of the wind resource. This thesis provides three contributions which tackle the problem and further improve the utilization of renewable generations.

Contribution: An optimal control model (IGM) handling vehicle-to-grid (V2G). This model consolidates nuclear, coal, natural gas, and renewable generation under a single controller, while maximizing the utilization of renewable energies. IGM effectively utilizes vehicle batteries as a distributed storage resource which makes V2G become a potential solution to the energy storage to further reduce intermittency and improve renewable energy utilization. Compare to

our previously proposed concept, *spatial smoothing*, which is based on the idea of connecting geographically distant wind turbines, V2G shows a more stable improvement. And by combining V2G with spatial smoothing, we raised the utilization of the renewable generation to a much higher level.

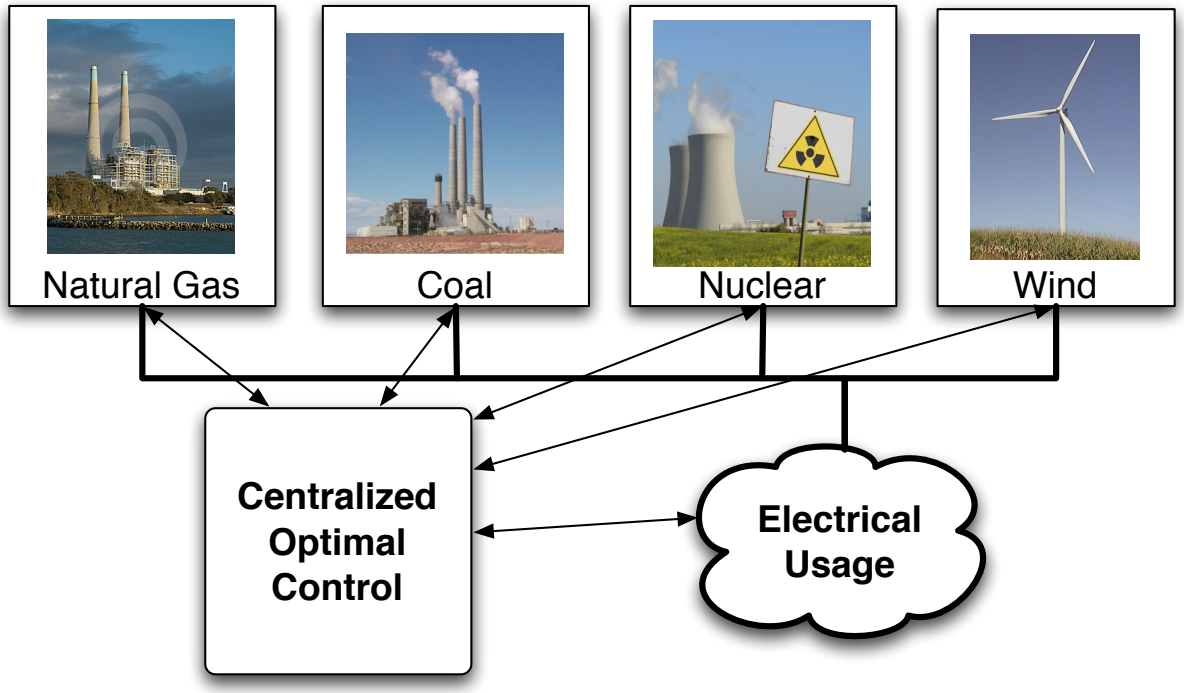


Figure 1: Overview of Integrated Generation Management (IGM).

In this thesis we propose a new concept called *integrated generation management* (IGM) to demonstrate the utilization potential of renewable energy. IGM is based on the concept of co-locating different generation techniques, an idea that has taken hold in particular for nuclear and coal generation. In this manner waste heat from the nuclear plant can be used to help more efficiently operate the coal plant. In IGM, we take this concept further. We consider consolidation of nuclear, coal, natural gas, and renewable generation under a single controller. These generation resources may be physically separated or geographically co-located or some combination of both. However, with IGM, the controller manages the output from all resources simultaneously to optimize a criterion (e.g. maximize wind usage, minimize power cost, etc.). Through the inclusion

of short-term storage, the efficiency of renewable generation usage and reduction in carbon-based generation can be further improved. An overview of the IGM concept is shown in Figure 1.

We demonstrate that through the use of IGM it is possible to significantly increase the penetration of wind energy into the grid and achieve a much higher utilization percentage of that wind energy. We also consider a pseudo-green generation source of nuclear generation as a baseline generation which has high power density and is low carbon emission. Through IGM, carbon emitting generation such as coal and natural gas are still important, but their overall generation is much reduced extending the lifetime of non-renewable generation.

IGM is predicated on long distance high efficiency transmission that depending on the distance leverages high-voltage direct current (HVDC) or high-voltage alternating current (HVAC) with flexible alternating-current transmission systems (FACTS). We first examine integrating wind turbines at a single location but also consider the impact of *spatial smoothing* by integrating geographically separated wind farms using HVDC/HVAC-FACTS. Spatial smoothing improves the availability of intermittent energy generation on average by averaging together sites with different intermittency characteristics. This typically results in less variability in the overall availability of the resource.

Additional, energy storage systems have been proposed to mitigate the intermittency of renewable generation for more effective integration into the grid. Currently, dedicated storage systems are too expensive to fabricate. However, with commodity plug-in hybrid electric vehicles (PHEVs) currently hitting the market, using the "vehicle-to-grid" (V2G) concept, these PHEVs can be utilized as a distributed storage resource, again leveraging high-efficiency transmission techniques. Thus, the PHEVs become a potential solution to the energy storage needs to further reduce intermittency and improve renewable energy utilization.

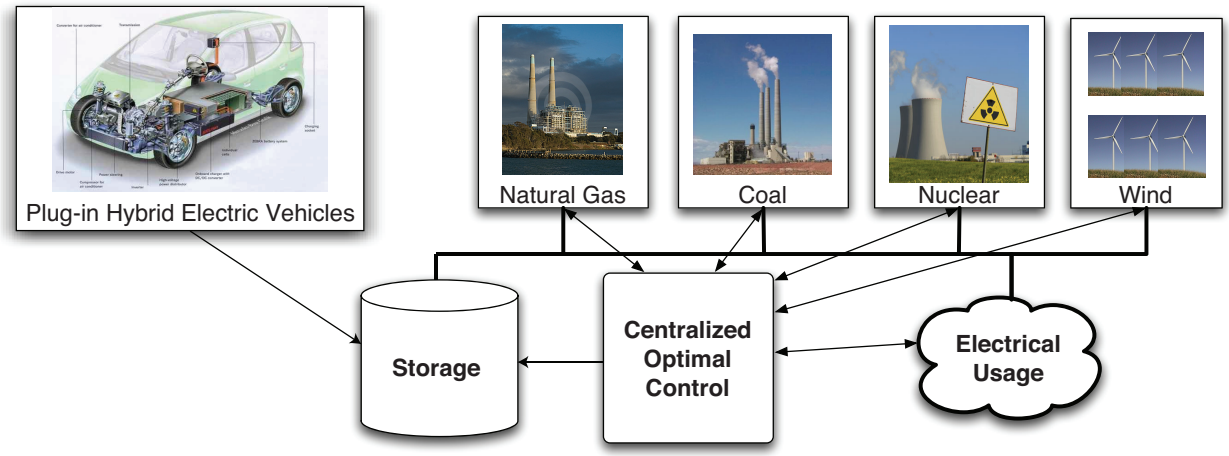


Figure 2: IGM with spatial smoothing and vehicle-to-grid capabilities.

In the thesis we describe the potential of using IGM in these scenarios that leverage spatial smoothing and vehicle-to-grid concepts (Figure 2) using wind as the renewable resource of interest. We size the generation of each resource, including nuclear, coal, and natural gas, which have the capability of outputting the necessary power when renewable generation is not available either in the short or long term, to maximize the utilization of renewable energy while minimizing the use of fossil resources. Through the use of linear programming [2] and based on complete knowledge of the wind and usage of the system we determine the potential of wind utilization and the requirements of the non-renewable generation sources.

Using IGM we demonstrate how wind generation efficiencies can reach 70% [3]. Spatial smoothing can increase the wind penetration while retaining the same efficiency. By integrating PHEVs as a resource we assume a scenario where when not in use these vehicles are plugged into the grid to be used as a storage resource. In effect the grid can "purchase" power from the PHEVs when needed to handle a lull in renewable generation and "sell" energy back to the PHEVs (at a reduced rate) when over generation occurs. In doing so, wind generation efficiencies can increase further. When combined together, considering wind generation of approximately 15% of the average load, we can increase the efficiency of wind energy used to 76% for a 1% market penetration of PHEVs expected by 2015 and to 86% for the 13% market penetration of PHEVs

expected by 2030. For nearly 30% wind generation of average load, these efficiencies are 63% and 68%, respectively.

The remainder of this thesis is organized as follows: Chapter 2 describes some background of smart grid and relevant related work to spatial smoothing, vehicle-to-grid, IGM, and wind energy utilization. Our model for determining the utilization in the system of the various generation systems and optimal control formulation is presented in Chapter 3. Power generation and battery constraints of the linear programming model are explained in Section 3.1.1 and Section 3.1.2. We then present the spatial smoothing case studies and results in Chapter 4. In Section 5.1 and 5.2 we show separately improvements over wind utilization on both single-day and full-year experiments, while Chapter 6 and Chapter 7 present some conclusions from our work and some future directions.

2.0 BACKGROUND AND RELATED WORK

2.1 FUTURE GRID

The power grid is undergoing significant changes driven by a number of needs such as the need for environmental compliance and energy reservation. More reliable power grid is needed while dealing with an aging infrastructure. The changes that are happening are particularly significant for the electricity distribution grid, where blind and manual operations, along with the electromechanical components, should be converted into a smart grid. This conversion should necessarily meet environmental targets, to accommodate a greater emphasis on user demand response, and to support PHEVs as well as distributed generation and storage capabilities.

Wind has been the fastest growing segment of the renewable industry. Over the past two decades, wind technology has improved significantly with turbines as large as 6 MW and costs below $2 million per megawatt of installed capacity; large wind farms with several hundred megawatt capacities are being deployed over several months. New wind or solar power generation facilities are being installed, interconnected, and commissioned in a relatively short time period, provided that the grid can handle the extra capacity. The economics of these resources are fast improving, reaching a close parity with fossil generation. Figure 3 shows a comparison of capital costs for new generation using various technologies [4].

However, these intermittent renewable resources pose many challenges for the grid and grid operators. Planning for transmission expansion to support increasing levels of wind generation in dispersed areas is essential to the growth of the wind sector. The increasing penetration of residential and municipal wind generation also imposes challenges on the existing distribution infrastructure and the system operator. Finally, forecasting and scheduling are needed to allow for making full use of generated power while ensuring the grid's properly functioning. The limited

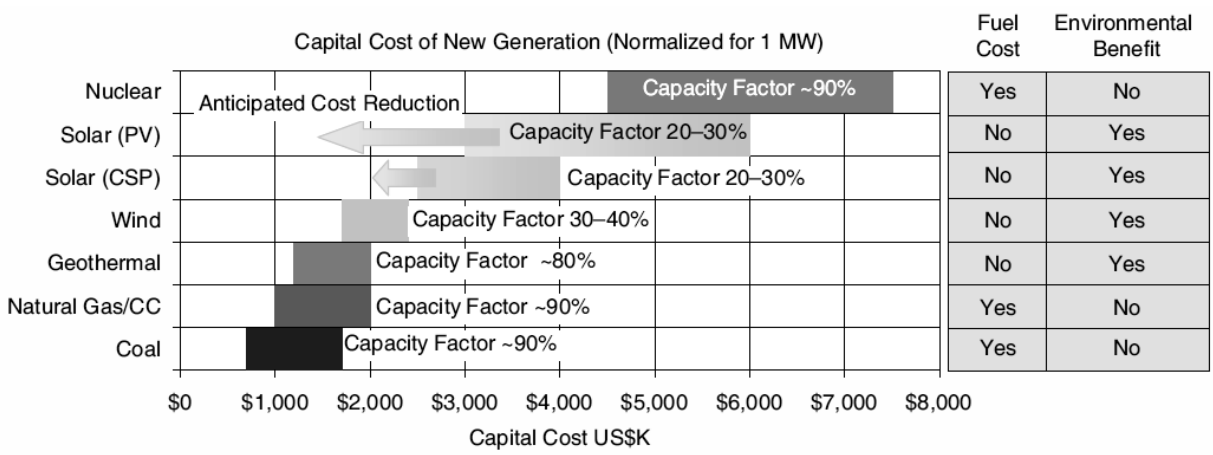


Figure 3: Cost comparison of Generations.

dispatchability and intermittent nature of renewable generation require grid operators to supply the additional ancillary services needed to maintain reliability and operational requirements.

2.2 INGERATED GENERATION MANAGEMENT

A major difficulty with using natural resources such as wind and solar power is their variable nature. In general for traditional generation sources such as coal fired plants or gas turbines the operator can choose the desired power production level. Wind power and solar power on the other hand are dependent on environmental factors, which can be problematic. Without energy storage the total power produced must be equal to the power being consumed at all times. Dedicated, fast-reacting storage is unfortunately very expensive and currently impractical at the sizes which would be required for loads of an entire city or region. In the absence of storage, wind and solar power generation must be backed up by traditional generation sources. This means that additional spinning reserve is needed, which adds to the cost of operation and also to the emissions [5, 6, 7]. The problem is exacerbated as wind penetration into the grid increases. Wind penetration is defined as

the ratio of the amount of wind power generated to the total energy delivered. For example, if 100 megawatt-hours (MWh) of wind energy are supplied and 1,000 MWh are consumed during a certain period, wind's penetration is 20 %. A possible alternative is to replace the use of large thermal units, which are slow to start up, with more expensive fast-starting distributed diesel generation. The benefit is that the diesel generators can be shut off when they are not being used [8].

Ingerated Generation Management (IGM) addresses this problem by sizing the generation capacities of various components of the system in proportion to the needs of the usage and the availability of the intermittent renewable resource. Its control signal to all possible generation resources in the grid provides most inexpensive yet secure combination dynamically, allowing best renewable utilization yet lowest cost. To improve the effectiveness of IGM we consider integrating the concepts of spatial smoothing of the renewable resource and leveraging an emerging distributed PHEV storage source within the grid. In the next two sections we provide some background on these ideas, respectively.

2.3 SPATIAL SMOOTHING

The idea for the spatial smoothing concept comes from probability theory. The potential wind power from any particular wind turbine at any time can be thought of as a random variable. In fact in many locations the possible power is often zero. So a single wind turbine is very unreliable. The idea is that by connecting many wind turbines we create a more reliable ensemble. A similar smoothing effect has been demonstrated with respect to power quality. It was shown that flicker and variations in the voltage produced by a single wind turbine can be cancelled out when many wind turbines are connected together [9].

For our work, we assume that any time even if some of the turbines are not producing power, some of the others must be. Statistically, the assumption can hold if the random variables representing the turbines are independent, and the total number of turbines is sufficiently large. If the variables are not independent then the state of one turbine tells us something about the states of the others. It is then possible that when one is not producing power neither are the others. It seems

logical to assume that turbines which are near each other could have this sort of dependency. Turbines which are far apart though should be independent.

The goal of this work is to measure the benefit of this spatial smoothing, using a simple model which focuses solely on this effect. Another, benefit of the IGM model which has been demonstrated is that in some cases using better wind resources located far away and long distance transportation, using technologies such as HVDC, can be cheaper than utilization of more local resources [10]. Of course, the implementation of long distance power transmission and spatial smoothing schemes requires some form of centralized control like IGM. IGM is predicated on long distance high efficiency transmission that, depending on the distance, leverages HVDC or HVAC with FACTS.

Through the use of IGM it is possible to significantly increase the penetration of wind energy into the grid and achieve a much higher utilization percentage of that wind energy. We also consider a pseudo-green generation source of nuclear generation as a baseline generation. Through IGM, carbon emitting generation such as coal and natural gas are still important, but their overall generation is much reduced extending the lifetime of non-renewable generation.

2.4 VEHICLE TO GRID

With commodity PHEVs, which include purely electric vehicles and plug-in hybrid gasoline/electric vehicles, reaching the market and projected market penetration of PHEVs becoming significant as soon as 2015, PHEVs as nodes on the smart-grid is already a reality. PHEVs in addition to their green stamp on the environment provide the benefit of a significant reduction in cost for fuel over fossil fuel based vehicles. However, PHEVs represent considerable challenges for several sectors of national infrastructure. Integration of PHEVs on the smart-grid termed “vehicle-to-grid” has already generated considerable interest to researchers as a significant new source of power loads. Additionally, with the limited range of electric vehicles and entirely new transportation infrastructure is required to provide “filling stations” for electric vehicles as well as new supply chains for battery replacements and many other logistical issues surrounding PHEVs [11].

However, PHEVs, while the potential equivalent of new appliance to enter our homes and workplaces, also provide the potential storage solution for integration of renewable energy generation. In conducting an analysis of market penetration of PHEVs and studying the power generation of a small city, PHEVs could provide the storage capacity to run the entire city for over a minute by 2015 and for more than a quarter of an hour by 2030.

This potential storage is highly valuable to the goal in successfully leveraging renewable power generation based on wind, solar, and other green energy sources. The common thread between many of these renewable energies is their intermittency, for which a "battery backup" to deal with generation lulls is important. Of course, electrical storage is not able to counter act entire days, or longer periods of generation outages due to calm or cloudy days.

In this paper, we are extending the IGM paradigm discussing a optimal control model to include utilizing the *vehicle to grid* (V2G) technique which can be more active in harnessing the wind energy even when compared to spatial smoothing. When a sufficient amount of PHEVs are connected to the power grid, the huge distributed battery system works as a buffer between renewable energy and the grid. When there is sufficient wind available in excess of the load requirement, extra power can be stored in the PHEV batteries under the dispatch of the centralized controller. The stored energy, together with the already existing battery power, serves as another source of electricity supply with very good load following, which eventually reduces the dependence of generation on conventional energy resources. Additionally, the PHEVs help to curb emissions not only by being fossil fuel free, but also through the reduction of fossil fuel powered electricity production. Typical case studies are provided in the standard [12] for interconnecting distributed energy resources with electric power systems.

Statistics show that to travel the same distance as a conventional car using one gallon of gas, an average cost around $1.50 (about half of the gas cost) is needed for a PHEV, based on the national average residential electricity price: 11.18 cents per kWh [13]. Also, by plugging their vehicles into the grid, end users can earn the electricity price difference if the V2G configuration enables them to sell (discharge) stored electricity to grid for a higher price at peak load, and buy (charge) back when the electricity is cheaper at lower demand. Together with tax reduction policies from the government and a more mature PHEV market through competition, these factors greatly encourage people to choose PHEVs when purchasing new vehicles and motivate attaching them onto the grid.

In the next section we describe our control methodology for IGM and how it extends to include spatial smoothing and storage integration from V2G principles.

3.0 THE IGM MODEL

3.1 OPTIMAL CONTROL MODEL

3.1.1 Common Resource Generations

Our model is based upon the IGM concept brought up by our previous work [3], where generation of several power sources is managed by a centralized controller in order to minimize the overall costs of generation, provided that total power production satisfies the usage requirement. It is commonly claimed that nuclear power is inflexible in its output, or in other words, performs poorly in load following. Though in the most recent practice in France (still under construction), the nuclear plant shows considerable response capability [14], we still consider it in our case as a baseline generation source which provides constant power production. Therefore, in order to meet the load requirements, the remaining portion of the power production must be matched together by the wind generator which has the lowest cost, the conventional source generators including coal and natural gas which can be time-variant according to demand but are much more expensive than the wind, and the PHEV battery cluster which from the grid perspective acts as both a power supplier and a temporary storage.

The injection of PHEVs into the power generation system adds complexity to dealing with the trade-off among those IGM sources mentioned above. Between coal and natural gas, the optimal solution is to maximize the usage of coal when the peak demand is met, because the coal's price is relatively smaller than natural gas. However, chances are that the changing velocity of the coal power generation is insufficient to compensate the fluctuations of the load, in which case more natural gas generation is applied because of its perfect load following characteristic. Wind power is easily the least expensive, so we want to make full use of it when available. In our previous

model [3], however, wind power is wasted when the supply exceeds the demand. This issue is improved when we introduce battery storage into the new model, with which surplus wind energy can be saved for later use. In addition, the controller is able to utilize the stored energy to minimize the usage of the coal and natural gas when wind energy falls below the load or not available at all as the batteries also react quickly to fluctuations of both load and wind. The optimization problem is thus to take full advantage of the batteries to maximize wind utilization and minimize natural gas usage between two conventional sources, while insuring the load demand is met.

The centralized controller applies linear programming with constraints of normalized real-life data to determine the optimal output combination of each energy source. The constraints are formed by describing the operating ranges of all the power generators, analysis of PHEV market penetration, together with our complete knowledge of wind power and daily electricity load. The controller is set to do optimization at both a one-day and a one-year period. By eliminating the influence of particular non-representative cases that may exist in short period operations, the latter optimization gives us a better knowledge of how the wind utilization would be in general.

To model the generation management system, we normalized the daily electricity usage with the maximum load being 1 and the value ranging from around 0.5 to 1 according to [15]. For the purpose of this work, we ignore the losses caused by distributed generation of wind power. Based on the normalization of load, an average of 0.75 unit electricity is produced by the grid between two adjacent time points, in this case a five minute interval.

For the power production of each resource, we allow coal generation to vary from 0.1 to 0.4, natural gas to vary from 0.05 to 0.4, wind to vary from 0 to 0.4, where W_t represents the amount of wind power available, and we fix nuclear at a level of 0.2 (approximately 27% of the average 0.75 consumption). Considering wind turbines have upper bound limits of generation from wind, we add a value of 0.4 to represent this restriction. For 2008 through early 2010, the nuclear power share of the overall United States electricity generation stayed around 20% [16]. By setting the nuclear production at a higher level (e.g. 27%) than the current condition, together with considering a relatively higher PHEV market penetration, we get a better picture of what the optimal control model can achieve in the future. These constraints can be expressed mathematically as:

$$
\begin{aligned}
0.1 \leq x_t^{\text{coal}} &\leq 0.4, \\
0.05 \leq x_t^{\text{gas}} &\leq 0.4, \\
0 \leq x_t^{\text{wind}} &\leq \min\{W_t, 0.4\}, \\
x_t^{\text{nuclear}} &= 0.2, \\
\text{for } 1 \leq t &\leq n
\end{aligned}
\tag{3.1}
$$

where x_t^{coal}, x_t^{gas}, x_t^{wind}, and x_t^{nuclear} represent the amount of power generated from coal, gas, wind, and nuclear sources, respectively at time t and n is the total number of samples in a day. In our experiments we assume 5-minute sampling, thus $n = 288$ for one day or n =105,120 for one year.

3.1.2 PHEVs as the Battery

The quantity of energy stored in the battery cluster q_t^{battery} varies between $0.2C_t^{\text{battery}}$ and C_t^{battery}, where C_t^{battery} is the total PHEV capacity plugged into the grid at time point t as shown in:

$$
0.2C_t^{\text{battery}} \leq q_t^{\text{battery}} \leq C_t^{\text{battery}}, \quad 1 \leq t \leq n \tag{3.2}
$$

where q_t^{battery} is the percent of maximum charge capacity contained in the storage element at time t. We do not allow the grid to draw q_t^{battery} below a minimum level of 20%, insuring the PHEVs' capability of daily running whenever they are detached from the grid. Capacity data for the experiment period is provided beforehand and will be discussed in Chapter 5.

Charging and discharging an individual battery cannot happen at the same time. However, in our model we are considering a large amount of batteries operating independently for periods of time instead of time points, so there can be both quantities of power used and stored, represented by u_t^{battery} and s_t^{battery} respectively. We also introduce a variable x_t^{battery}, as shown in Eq. (3.3), representing how much battery power is drawn or stored, the sign of which tells whether charging or discharging is dominant for that time period. Another important factor is the storage capacity fluctuation caused by attaching or detaching vehicles to or from the grid, which leads to jumps of

battery power (j_t^{battery}) on grid. β_t is the ratio of the power jump to the capacity change. Relationships of those conditions are also expressed in Eq. (3.3).

$$\begin{aligned} x_t^{\text{battery}} &= u_t^{\text{battery}} - s_t^{\text{battery}}, \\ j_t^{\text{battery}} &= \beta_t (C_{t+1}^{\text{battery}} - C_t^{\text{battery}}), \\ q_{t+1}^{\text{battery}} &= q_t^{\text{battery}} - x_t^{\text{battery}} + j_t^{\text{battery}}, \\ &\text{for } 1 \leq t \leq n-1 \end{aligned} \tag{3.3}$$

Coefficient β_t is formulated in Eq. (3.4). We set the average power level to 25% of the capacity of the battery of each vehicle plugged into the grid, which is the value of the coefficient when the total on-grid capacity increases. However, we cannot decide the unplugging coefficient by simply assigning another constant value. A legitimate approach is to set it as the ratio of overall power to overall capacity, which gives an average level of PHEV battery power on grid at the time vehicles are detached.

$$\beta_t = \begin{cases} 0.25, & C_{t+1}^{\text{battery}} - C_t^{\text{battery}} \geq 0 \\ q_t^{\text{battery}} / C_t^{\text{battery}}, & C_{t+1}^{\text{battery}} - C_t^{\text{battery}} < 0 \end{cases} \quad \text{for } 1 \leq t \leq n-1 \tag{3.4}$$

The second expression in Eq. (3.4) contains q_t^{battery} that is relevant to x_t^{battery}, one of the decision variables as defined in Eq. (3.3). In order to apply linear programming to our model, based on the sign of $C_{t+1}^{\text{battery}} - C_t^{\text{battery}}$ since capacity data is provided, we determine before the optimization process whether to use β as a factor to set the constraints or to update the cost function matrix.

Also we should allow a 5% error for the overall power production P_t to change between 0.95 and 1.05 times the total load at any time. This restriction is formulated in Eq. (3.5) with x_t^{nuclear} replaced with the constant 0.2.

$$\begin{aligned} P_t = x_t^{\text{coal}} + x_t^{\text{gas}} + x_t^{\text{wind}} + x_t^{\text{battery}} + 0.2, &\quad 1 \leq t \leq n \\ 0.95 L_t \leq P_t \leq 1.05 L_t, &\quad 1 \leq t \leq n \end{aligned} \tag{3.5}$$

A major reason we introduce storage into the IGM is to compensate the poor load following of coal power generation such that the usage of expensive natural gas can be minimized. This brings up another set of restrictions which is known as dynamic characteristics. Wind is not the factor we want to control but to utilize, in other words, we use wind as long as it is available. So the dynamic characteristics of only coal, natural gas and batteries are considered. For our model, the optimization deals with data at five minute intervals. Within that length of each time step, we set the coal production to change within the limit of 0.003 (0.75% of the maximum), the gas to change within the limit of 0.03 (7.5% of the maximum) and the battery to be charged or discharged within the same limit of 0.15 (75% of the maximum). Eq. (3.6) describes these requirements mathematically.

$$
\begin{aligned}
|x_{t+1}^{\text{coal}} - x_t^{\text{coal}}| &\leq 0.003, \quad 1 \leq t \leq n-1 \\
|x_{t+1}^{\text{gas}} - x_t^{\text{gas}}| &\leq 0.03, \quad 1 \leq t \leq n-1 \\
0 \leq u_t^{\text{battery}} &\leq 0.15, \quad 1 \leq t \leq n \\
0 \leq s_t^{\text{battery}} &\leq 0.15, \quad 1 \leq t \leq n
\end{aligned}
\tag{3.6}
$$

3.1.3 Cost Function

Within the above discussion, all the real world requirements of the IGM are formulated mathematically for our model. All sets of specific values that satisfy the requirements of the variables are feasible solutions to make the controller work correctly. In many cases, the number of feasible solutions is infinite. To find out the optimal solution, in our case which is the cheapest one, different prices are applied to each unit of power production of different sources. Since nuclear production is fixed, cost of which is thus fixed and will not change the outputs of other sources whether it is included in the cost function or not.

The prices of nuclear and coal are tied at \$0.04 per kWh, making the modern and traditional resources as two cheapest forms of energy production. Currently wind power (\$0.08 per kWh) came in slightly cheaper than natural gas (\$0.10 per kWh). While we can foresee its very low running cost in the future we regard it as the cheapest generation sector in the model. Also, there is a higher degree of uncertainty in cost with wind energy due to poor and varying data regarding the

useful life of the facilities and their capacity factors. In this thesis we consider and use the average of the data points in the modelling.

According to [17], for generating every 10^6 Btu, average cost of coal is \$2.27 while \$5.43 for natural gas. Only relative costs are needed to determine the optimal output; so all costs are normalized with the cost of coal being 1. With existing technology, the capital cost for wind generation is high and takes up most of the total cost as there is hardly any fuel cost. However, in our model the unit cost of wind is set to a relatively low level as we are expecting optimistically new wind turbine technology and more mature industry. In the V2G scenario, end users of the grid are expecting to buy the electricity at a lower price and sell it at a higher price. And from the perspective of the grid, this is a reasonable assumption as there exists certain cost (e.g. maintenance) for using the distributed PHEVs as its storage component. Eq. (3.7) gives the normalized cost function, which is linear.

$$\sum_{t=1}^{n} x_t^{\text{coal}} + 2.5 \sum_{t=1}^{n} x_t^{\text{gas}} + 0.1 \sum_{t=1}^{n} x_t^{\text{wind}} + \sum_{t=1}^{n} u_t^{\text{battery}} - 0.8 \sum_{t=1}^{n} s_t^{\text{battery}}$$

The IGM problem here is to minimize the linear cost function specified in Eq. (3.7) subject to a set of linear constraints from Eqs. (3.1)-(3.6). This problem can be efficiently solved by any standard linear programming algorithm.

Our model requires two types of data. It requires usage data which specifies the amount of power being consumed by the load at any particular moment and data that specifies the amount of energy which can be derived from wind at any particular moment. The wind data should tell the maximum amount of power that could be produced. Then using the optimization method described above, the amount of power which is actually produced can be determined. It is important that the data should not be the actual output from wind turbines. In that case the data would already have been filtered by the utility removing all unusable potential.

Significant areas of the world have mean annual wind speeds of above 4-5 m/s (metres per second) which makes small-scale wind powered electricity generation an attractive option. It is important to obtain accurate wind speed data for the site in mind before any decision can be made

as to its suitability. The power in the wind is proportional to the cube of the wind speed, and obviously the air density - which varies with altitude.

The actual power that we can extract from the wind is significantly less the maximum value, which depends on several factors, such as the type of machine and rotor used, friction losses, and other power losses in the pumps or other equipment connected to the wind machine. There are also physical limits to the amount of power that can be extracted realistically from the wind. It can been shown theoretically that any windmill can only possibly extract a maximum of 59.3% of the power from the wind (this is known as the Betz limit). In reality, this figure is usually around 45% (maximum) for a large electricity producing turbine and around 30% to 40% for a wind pump [18].

Another advantage of our linear programming model is that it can be conveniently scaled. After normalization a system with a 300 GW load is equivalent to a normalized model of a system with a 500 MW load. In particular, our model allows us to study the effects of different levels of network integration on the wind power usage. By averaging wind power from different numbers of wind turbines or sources our model can simulate different size networks being controlled with an IGM strategy.

In the next chapter we examine the use of this model in several scenarios that utilize spatial smoothing, V2G, and a combination of the two.

4.0 SPATIAL SMOOTHING CASE STUDIES

The model described in the previous section finds the most cost efficient operation strategy for the system given the amount of wind power available and given the load. By experimenting with the available wind power we try to demonstrate the possible benefits of the IGM control and spatial smoothing. The following experiments do not include any storage in the optimal control model.

4.1 TURBINE LEVEL STUDY

To investigate the impact of spatial smoothing we first studied spatial smoothing at the individual wind turbine level, a preliminary version of this study was published in [3]. The wind data used for this experiment all comes from the Western Wind Integration Study [19]. The data that was used is the SCORE-lite power output. It was produced by 3TIER and the National Renewable Energy Laboratory (NREL), using wind speed data, and attempting to incorporate the stochastic nature of real output power. Each NREL site represents a local cluster of ten 3MW turbines that together produce a total output power of 30MW. The data is on ten minute intervals and covers the entire year from January 1, 2006 until December 31, 2006. For the purpose of processing with the linear programming algorithm the data was broken into one day intervals which were processed individually.

The tests were run with several different integration scenarios. The tests vary the number of wind turbine clusters connected to the grid between one and ten using clusters within a single wind farm in Texas as well as throughout the western region. By conducting these individual tests we could evaluate the extent to which spatial smoothing can occur in a single wind farm compared with more geographically distant locations.

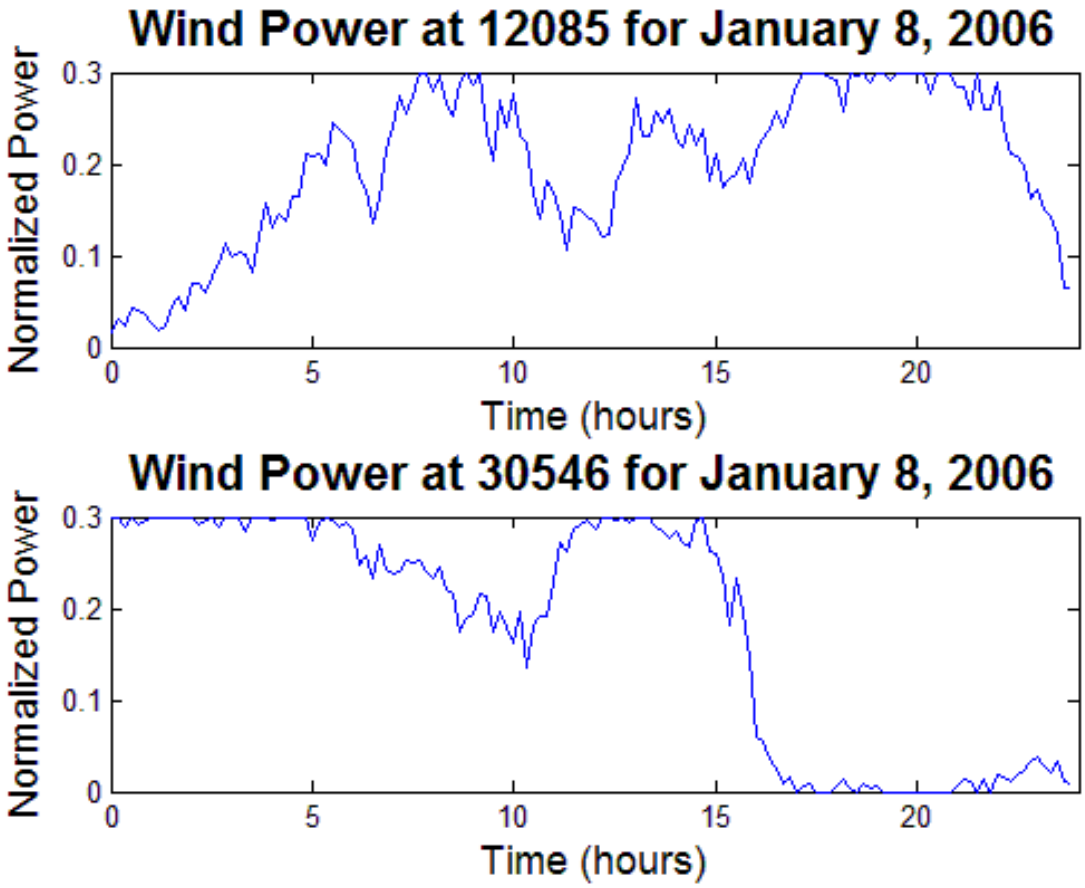


Figure 4: Wind curves at two sites in the west.

Example wind power curves, from January 8, 2006, for two locations in the western United States are shown in Figure 4. The power was normalized to a maximum of 0.3. The identifier numbers indicate the site numbers as assigned by the Western Wind Integration Study [19]. At both locations over the course of a single day wind power varies from very small values to the maximum value. The unpredictability of these variations is exemplified by the quick descent at around 16 hours (4 pm) in the second curve.

For the case study West, wind power curves from ten locations in the West were averaged together as shown in Figure 5. Comparison of Figure 4 and Figure 5 illustrates the impact of spatial smoothing. The averaged curve never falls below about 0.12 and never goes higher than

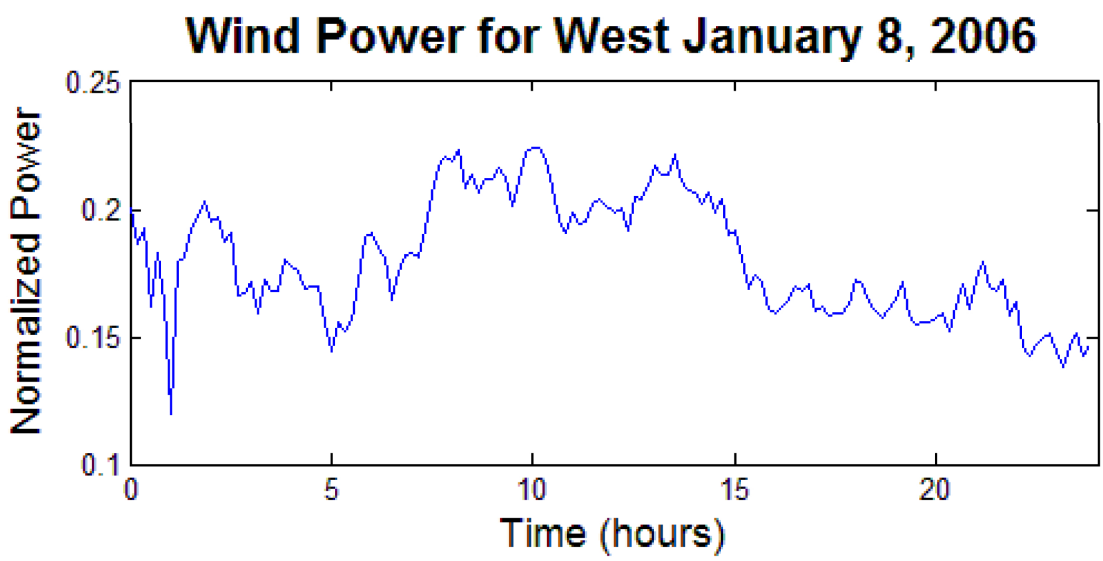


Figure 5: Wind curves for the average of the two sites in the west.

0.23. It is much more consistent than the curves for the individual sites. This consistency is of great value for system operations and optimization of its integration into the grid due to its predictability.

To evaluate the impact of wind generation on a real load, we used usage data from the New Hampshire Electric Co-Op [15]. This data provided hourly usage for several full days. To match the wind usage statistics at 10 minute intervals we used the averaging technique described in [20], which had been previously applied to solar energy systems. The technique in [20] is designed to provide interpolated data for finer resolution while maintaining the average usage at the original resolution.

The two electrical usage curves which were used in the experiments are shown in Figure 6. Many of the usage curves in the dataset were quite similar, we selected two with the most distinct characteristics enumerated as usage curves 1 and 4 in the figure. Curve 4 has a different shape and a higher maximum utilization centered around 7pm than curve 1. For these experiments we utilized the parameters from Eq. (3.1), where at maximum generation, wind energy would provide 40% of the generation to satisfy the maximum load of the system. Experiments were conducted

using the wind energy for each day over the course of the entire 2006 year applied to the same usage curve and averaged together.

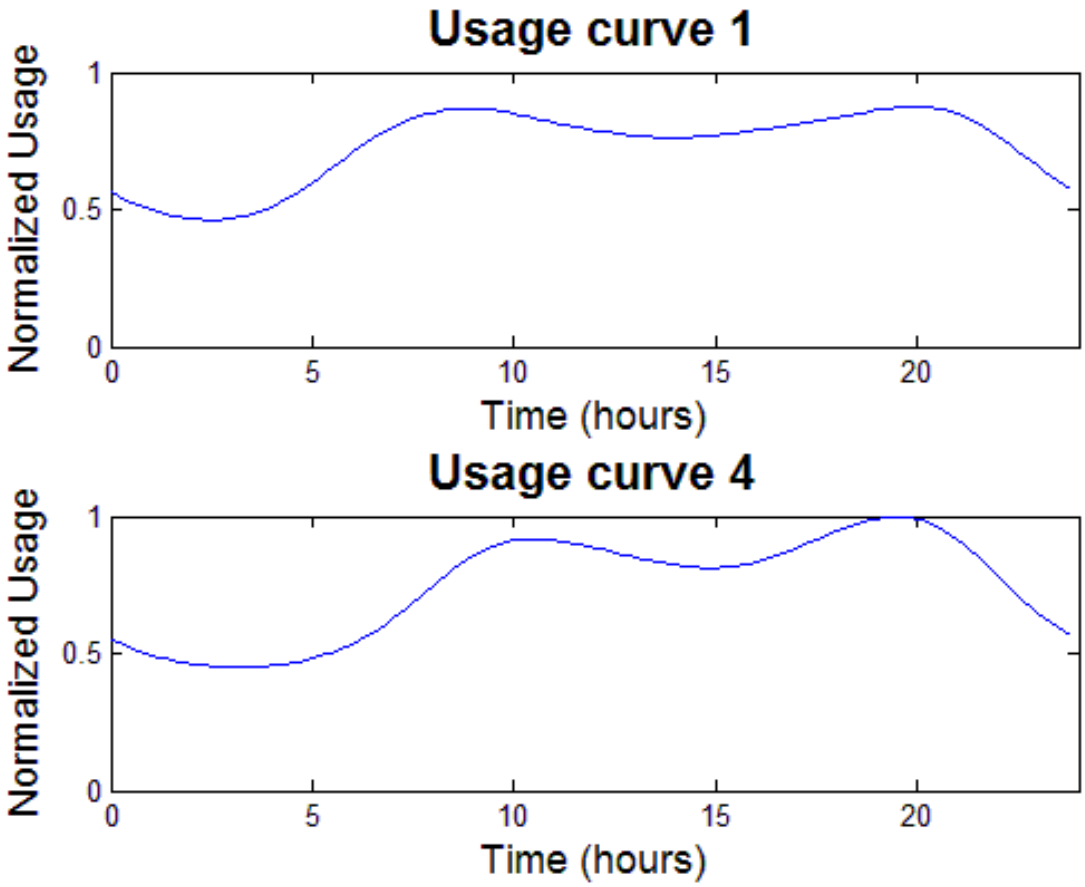


Figure 6: Electrical usage for August 29 and September 1, 1997 from the New Hampshire Electric Co-Op [15].

First we examined geographically local—within the same wind farm—wind sites in Texas. These results show a nominal benefit from spatial smoothing. Both load curves saw an increase of about 2% generation coming from spatial smoothing compared to the average with an increase in wind utilization percentage (percent of available wind energy that was used to satisfy actual load). The bulk of the fossil reduction came from natural gas generation, which according to the formulation is the more costly generation method.

Table 1: Impact of Spatial Smoothing for Geographically Local Turbines within Texas.

	Average		Spatial Smoothing	
Load Curve	Curve 1	Curve 4	Curve 1	Curve 4
Wind Generation	13.7%	12.0%	15.9%	13.8%
Coal Generation	41.7%	39.8%	41.0%	39.6%
Gas Generation	17.7%	21.7%	16.3%	20.1%
Nuclear Generation	26.9%	26.5%	26.9%	26.5%
Wind Utilization	64.0%	57.4%	67.5%	60.3%

Using the control formulation from Chapter 3 the system is able to leverage almost two-thirds of the available wind energy for consumption. Interestingly, the load/usage curve makes a big difference to the amount of wind energy that can be leveraged. We found the wind energy to be quite periodic on a day to day basis. To more it differs from the load/usage curve appears to impact to amount of wind energy that can be leveraged, in this case by just over 5% as can be seen in Table 1.

Next we examined geographically distant wind sites throughout the Western US. Table 2 compares the average utilizations across five sites in the west with the same sites using spatial smoothing. For the average case, the wind generation and utilization was lower and gas and coal generation was higher in the west than in Texas. However, when employing spatial smoothing, the west beat the Texas scenario in terms of wind, coal, and gas-based generation by a considerable margin and was nominally the same in terms of wind utilization. Thus, with less raw wind availability but a larger geographical smoothing region, as expected, the wind usability improves. To determine scalability, we examined the case when more sites were used for spatial smoothing, our results indicate that four or five sites is sufficient. For example with ten sites the wind utilization only increases to 68.3% and 58.9% for curves 1 and 4, respectively or less than half a percent improvement.

Table 2: Impact of Spatial Smoothing for Geographically Distant Turbines Throughout the Western US.

	Average		Spatial Smoothing	
Load Curve	Curve 1	Curve 4	Curve 1	Curve 4
Wind Generation	12.4%	10.6%	19.6%	16.3%
Coal Generation	42.6%	40.3%	39.8%	39.8%
Gas Generation	18.1%	22.6%	13.7%	17.3%
Nuclear Generation	26.9%	26.6%	26.9%	26.5%
Wind Utilization	57.3%	50.4%	68.0%	58.5%

Comparison of the above results show averaging that the more dependent random outputs produced by wind turbines which are located nearby, gives less benefits. Better spatial smoothing is achieved when wind turbines are spread out over a large region and their outputs are less dependent.

4.2 REGIONAL LEVEL STUDY

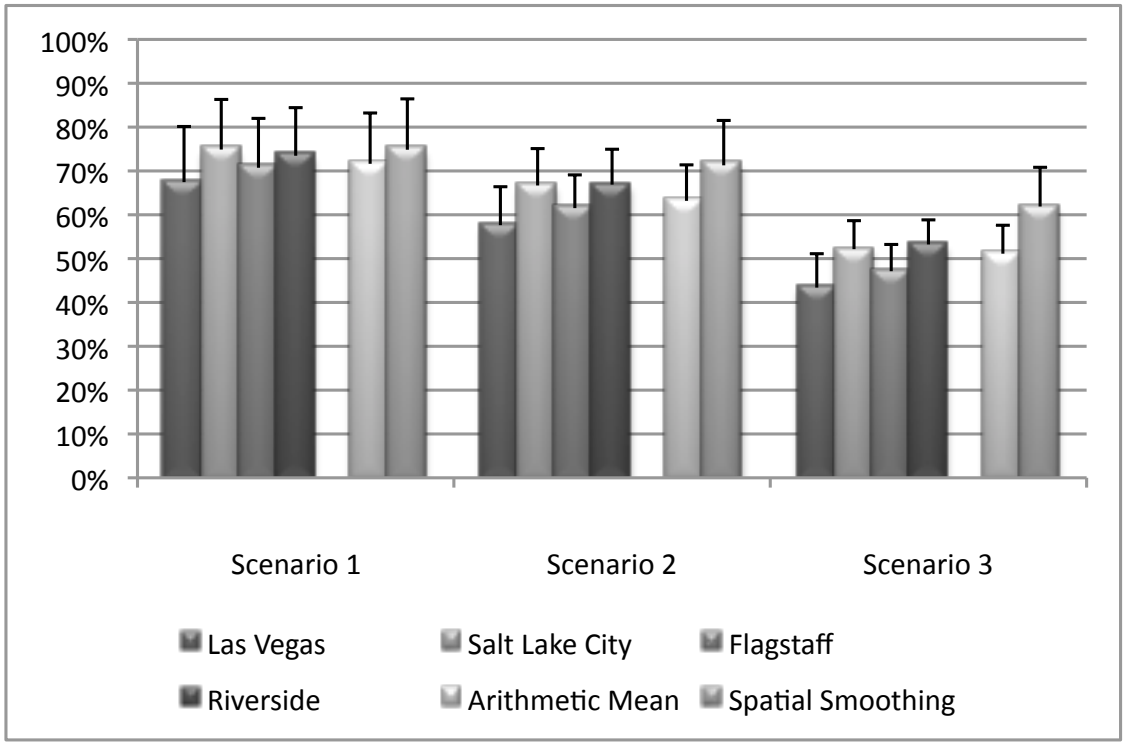
To further explore the impact and potential of spatial smoothing on effective wind power utilization we expanded on the west spatial smoothing study. We consider spatial smoothing of wind generation from the regions near the cities of Las Vegas, Salt Lake City, Riverside, and Flagstaff. To simplify the experiment a single usage curve was created that is the average of the daily usage available from the NHEC [15] that closely resembles usage curve 4 from Figure 6, which yields to more conservative results of wind utilization in Section 4.1. In addition to the wind generation capacity of 0.4, 40% of the maximum load (scenario 1), we also considered wind generation capacity of 60% (scenario 2), and 90% (scenario 3). The results are shown in Figure 7. All charts have individual values for each of the four cities, arithmetic mean, and spatial smoothing compu-

tation for each of the scenarios. The error bars shown in these charts are related to electric storage studied in Chapter 5 and can be ignored for the purposes of this discussion.

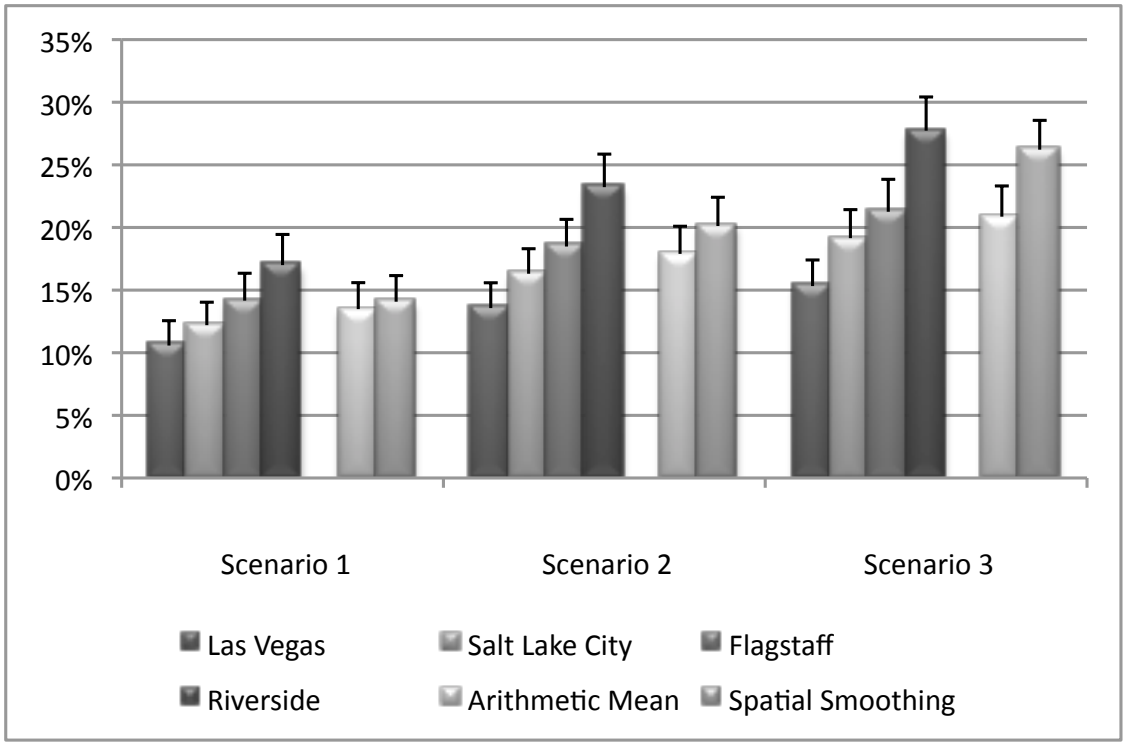
Figure 7(a) shows the wind utilization percentage for the three scenarios. The spatial smoothing has an increasingly valuable impact as the amount of wind power available is increased. The biggest step improvement appears to be between scenarios 1 and 2. The wind utilization percent only falls from about 75% to 71% and using spatial smoothing exceeds the utilization of any of the individual sites alone and exceeds the average by about 10%. For scenario 3 the spatial smoothing impact is even more dramatic, but the utilization percentage drops to just over 60%. However, the utilization of scenario 3 is still comparable with the usage curve 4 results from from Tables 1 and 2.

The resulting wind power generation, shown in Figure 7(b), is highly variable depending on the region with the smallest wind generation in Las Vegas and the largest in Riverside. As the grid penetration of the wind increases the impact of spatial smoothing increases. For scenario 3, using spatial smoothing all four regions would leverage more than 25% wind power just shy of best wind region of Riverside. The generation from natural gas (Figure 7(c)) shows significant reduction due to spatial smoothing but the reduction due to additional wind penetration is more tempered than expected. Conversely, the generation from coal (Figure 7(d)) is less impacted by spatial smoothing being just as likely to increase as decrease compared to the average. However, the total coal-based generation decreases considerably as more wind energy is available.

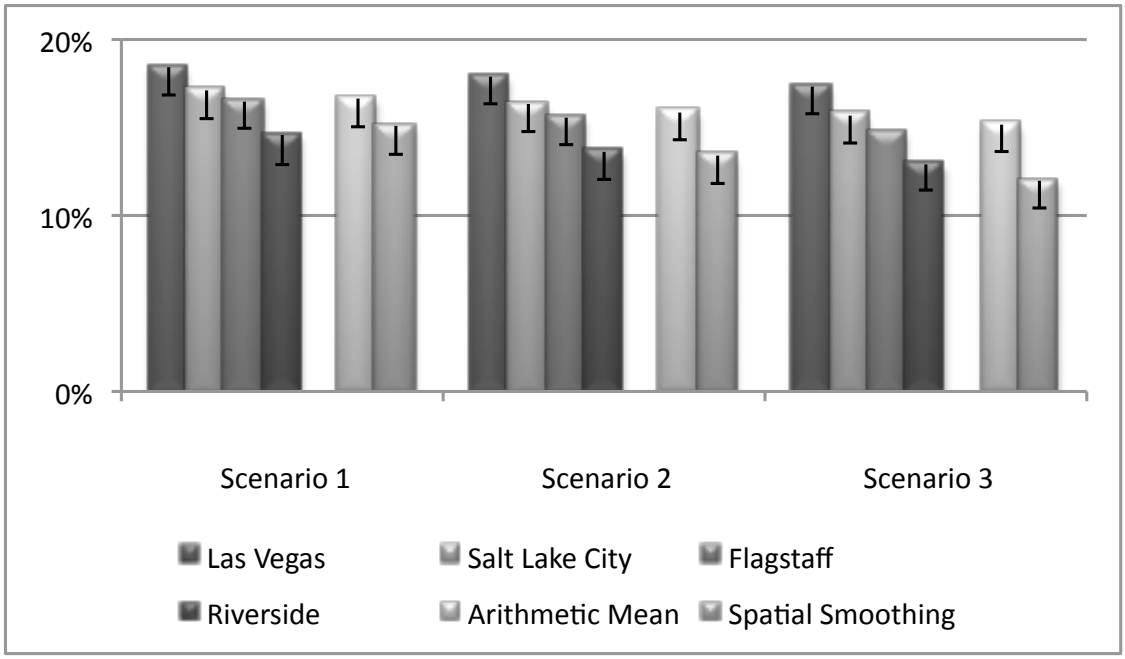
These results imply that the optimization formulation is capable of leveraging more wind energy to replace slowly reacting but relatively cheap fossil-based energy. In contrast, spatial smoothing, as expected, limits the volatility of the wind production allowing an improvement in the fast reacting, expensive fossil-based generation of natural gas. In the following section, we will examine the impact of incorporating storage into this system to further improve efficiency of wind integration.



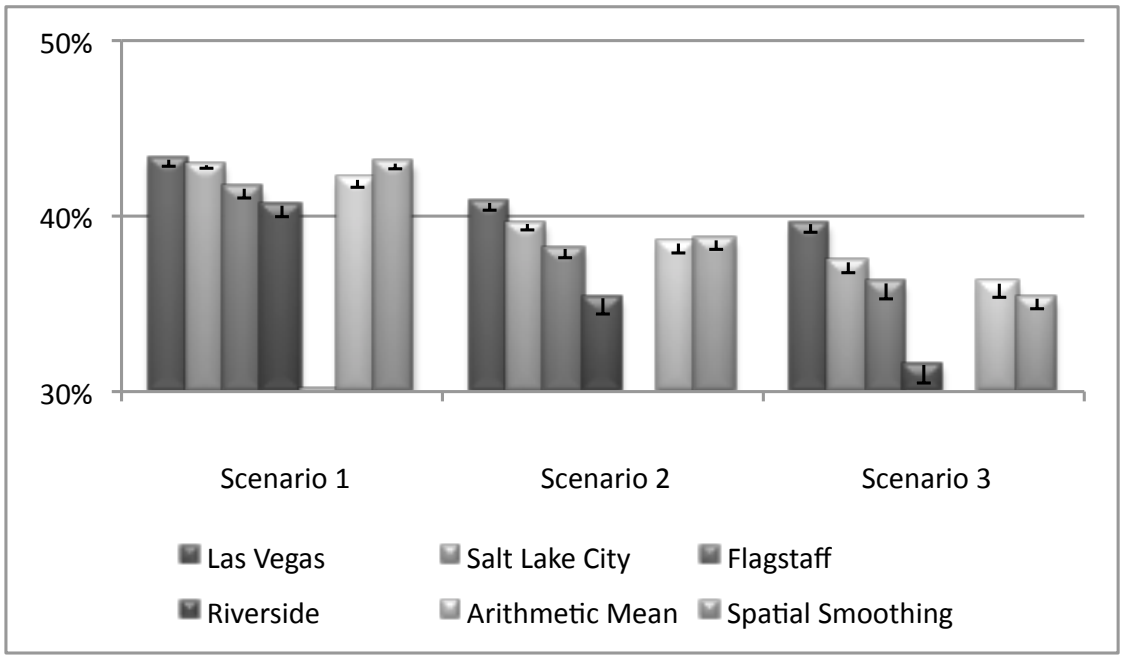
(a) Utilization of available wind.



(b) Generation from wind.



(c) Generation from natural gas.



(d) Generation from coal.

Figure 7: Evaluation of wind penetration scenarios where maximum wind generation is equivalent to 40%, 60%, and 90% of the maximum usage/load.

5.0 INTEGRATION OF ELECTRICAL STORAGE WITH V2G

In this section we examine the impact of leveraging the storage potential of PHEVs for harnessing wind energy in a case study using Las Vegas. First we studied the impact of storage on two particular days with different wind properties and then examine the impact of different storage penetrations over the course of an entire year.

As described in Chapter 3, specific data is needed to constrain the cost function in order for the controller to output the optimal strategy. Aside from the numbers we included in the expressions, data of wind power (W_t), load (L_t) and PHEV capacity (C_t^{battery}) used in the experiment is explained as follows.

Given that the power available in the wind is proportional to the cube of its speed, we used the raw wind speed data of Las Vegas in year 2009 from National Climatic Data Center [21] instead of the actual wind power from wind turbines because it is required in our experiment that the potential of wind generators is fully exploited, or we get only a portion of the wind power with unused part filtered by the controller.

Using the city of Las Vegas as an example based on statistics on number of registered vehicles and electrical usage from 2009 in [22] we determined the daily energy usage. Looking at the number of registered vehicles [22] and considering the expected market penetration of PHEVs as 1% by 2015 and 13% by 2030 [23], using an average battery capacity of different currently available and soon-to-launch PHEV offerings we determined the potential storage capacity from the PHEV vehicles in Las Vegas.

To determine what percentage of the PHEVs, and thus the storage, is connected to the grid at any particular time we start with the assumption that the average number of vehicles parked and thus plugged into the grid is 95% [24]. We considered several scenarios where the number of vehicles connected to the grid varied between 90% and 100% with an average of 95%. In the

results presented here we assumed the storage followed the usage curve[1]. The usage curve used the raw kWh load from [22] but was normalized to the shape determined from data obtained from [15] as described in Section 4.2. Finally, as described in the formulation from Eq. (3.2) we assume the vehicle storage can never be drawn below 20% of the currently available capacity on average, see Chapter 3.

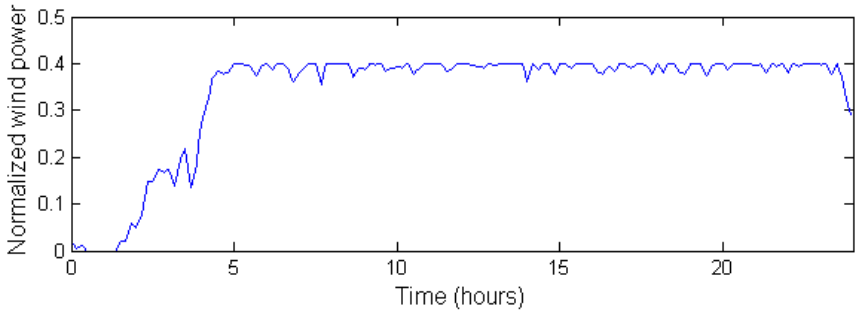
5.1 IMPACT OF STORAGE IN SINGLE DAY EXPERIMENTS

To examine the impact of storage provided by PHEVs towards wind utilization we studied the behavior of the storage for the two extreme cases of high and low wind availability displayed in Figure 8. In both cases storage is utilized, charging, and discharging to the extreme capacity as shown in Figs. 8(c) and 8(d), in particular banking energy in nighttime hours. In the heavy case, some wind energy is even banked at mid-day due to the lull in energy usage. In the light case, there is hardly any spare wind energy generated for storage between 9 am and 11 pm as the electricity consumption stays high.

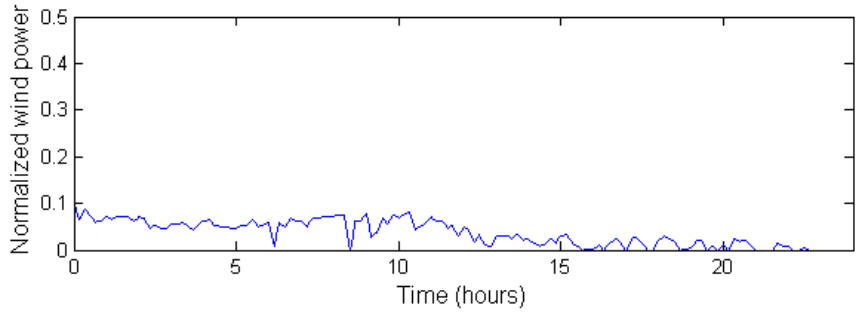
In addition to improving the amount of usable wind energy, it is expected that the storage will increase the use of slowly following coal energy in place of the more expensive but faster following natural gas. In effect by providing a reserve source and sink allowing the storage allows the fossil energy ramp up and down more slowly favoring the less expensive coal.

PHEV owners can also derive significant benefit from reducing dependency on gasoline thus reducing the cost, and other incentives like government policy. By connecting bi-directionally to the smart grid, electric vehicles selling electricity back to the grid may become possible in the near future, ultimately providing consumers with the choice to buy energy at low rates and sell at high.

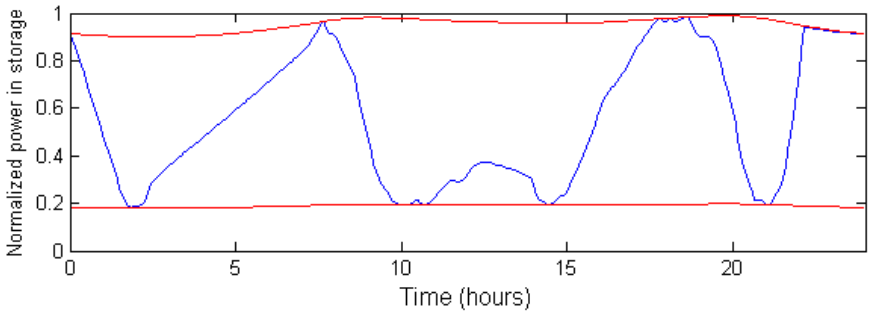
[1] We found that results from this scenario and the most conservative scenario where storage was inversely proportional to load did not vary significantly.



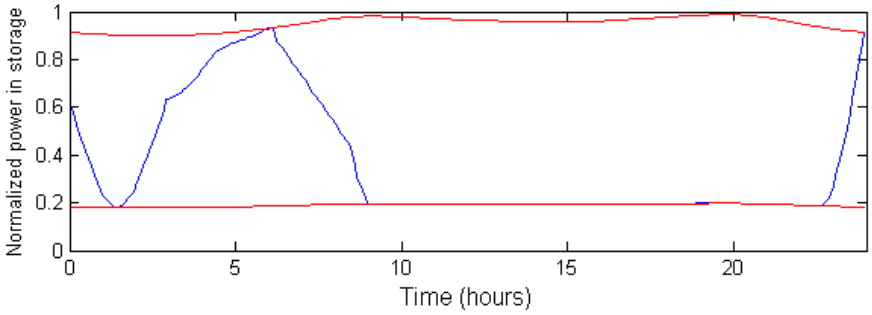
(a) Heavy wind power.



(b) Light wind power.



(c) Storage utilization for heavy wind power.



(d) Storage utilization for light wind power.

Figure 8: Storage utilization for heavy and light wind.

5.2 IMPACT OF STORAGE IN FULL YEAR EXPERIMENT

To better evaluate the improvements on wind utilization by applying the V2G technique, we conducted a one year experiment to figure out the generation distribution over different sources. Influences from particular cases and marginal effect can then be eliminated by averaging results out of such a long period test. We did some approximations on data of Las Vegas to obtain total PHEV battery capacity out of data provided by [22], from where we know that Las Vegas uses 23,030,806 MWh per year, which leads to 63,098 MWh per day and 219.1 MWh per five minute interval. Also, with an estimated number of 0.33 million vehicles in Las Vegas in 2015 and a research finding of 1% PHEV market penetration by then [23], we estimated the total capacity in Las Vegas by 2015 to be 65.7 MWh (for each five minute interval) which is 30% of the load. Capacities of larger penetration scenarios can be easily obtained since they are proportional to the penetration percentages.

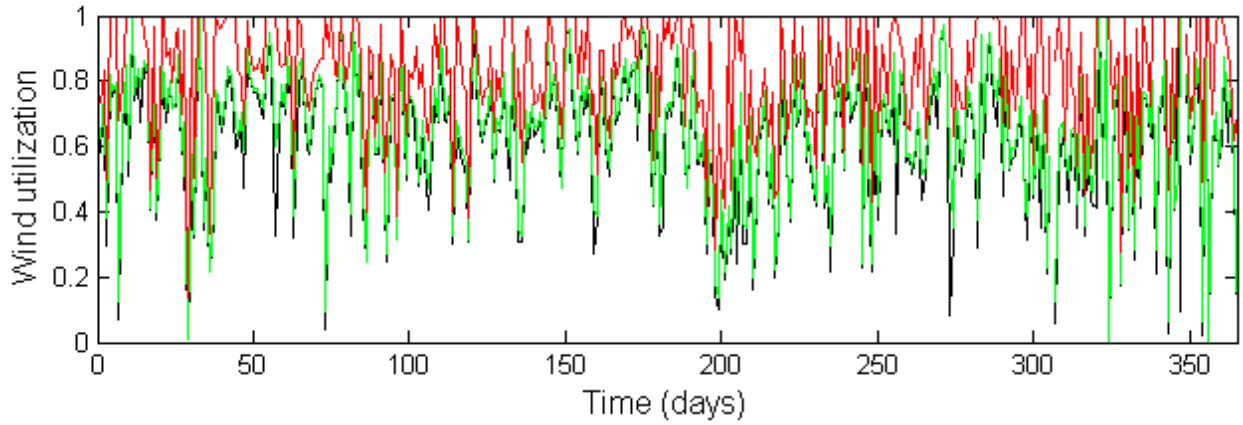


Figure 9: Improvements of wind utilization of year 2009 with different PHEV market penetrations: Scenario without storage (black), with 1% penetration (green), with 13% penetration (red).

To see the impact of storage on utilization of wind power we plotted the wind utilization in Figure 9 where the curves represent systems without storage (black), with the storage provided by

1% (green) and 13% PHEV (green) penetration. Even with 1% PHEV penetration, the impact of the storage is considerable and when extended to 13% the benefits are similarly improved.

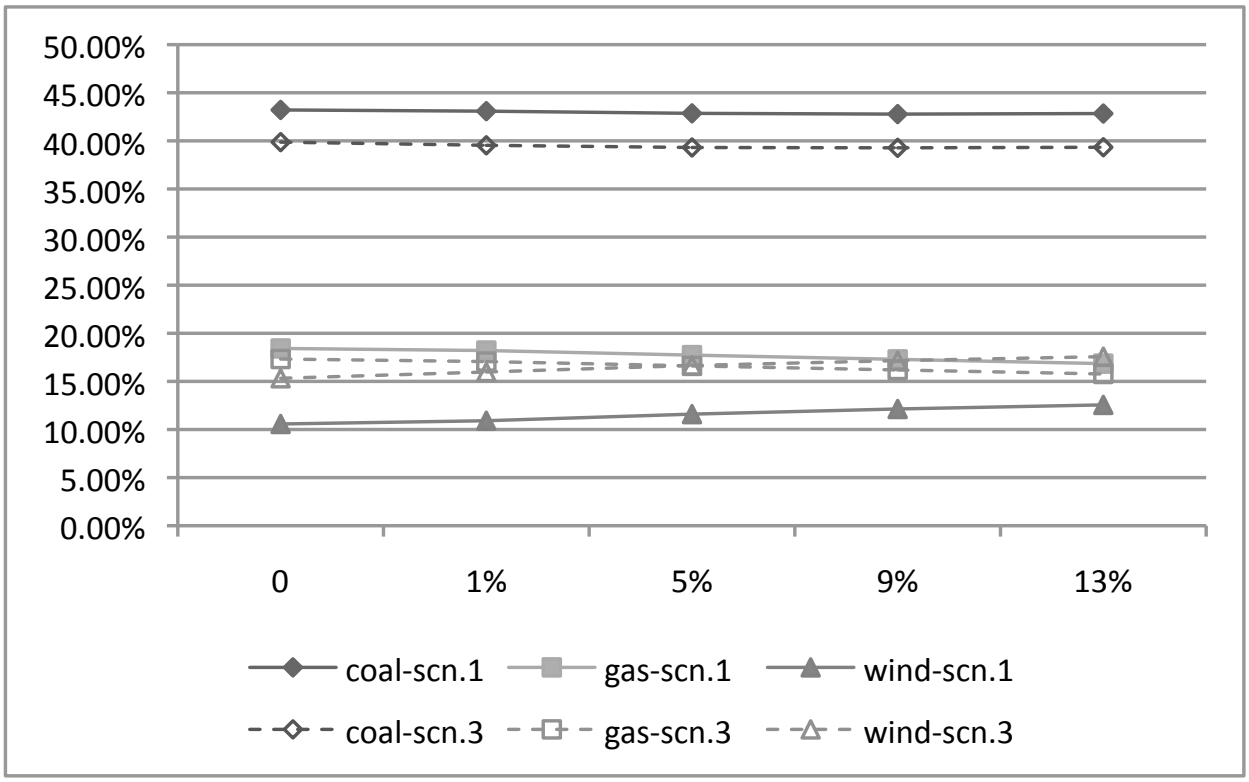


Figure 10: Impact of various levels of storage on wind, coal, and gas generation for two different scenarios of wind integration for Las Vegas.

The basic scenario without V2G and storage integration varied between 1% and 13% PHEV market penetration were tested for two different levels of wind generation (scenarios 1 and 3 from Section 4.2 and the results are shown in Figure 10. The addition of storage increases the power generated from wind and reducing the power generated from gas and slightly reducing the power generated from coal. While the starting points for scenarios 1 and 3 are offset as discussed in Section 4.2, the trends are similar for both scenarios.

Another metric to determine the success of this approach is to examine the improvement in percentage of the wind energy that is generated that can actually be used (wind usage efficiency) when storage is increased. As expected, the percent of wind utilization is improved using the additional storage as shown in Figure 11. Just by adding storage from PHEV market penetration, at 1% penetration the utilization increases by 3-4% and at 13% the improvement is 13-16% depending on scenario.

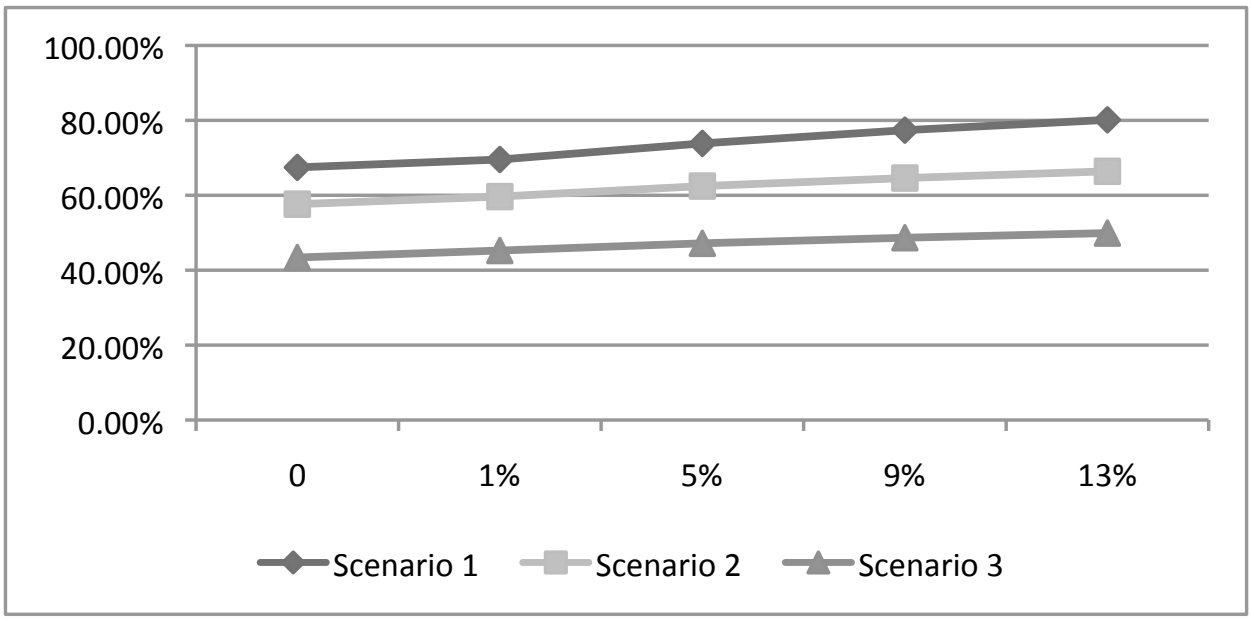


Figure 11: Impact of various levels of storage on wind utilization for three different scenarios of wind integration for Las Vegas.

5.3 COMBINING SPATIAL SMOOTHING WITH STORAGE

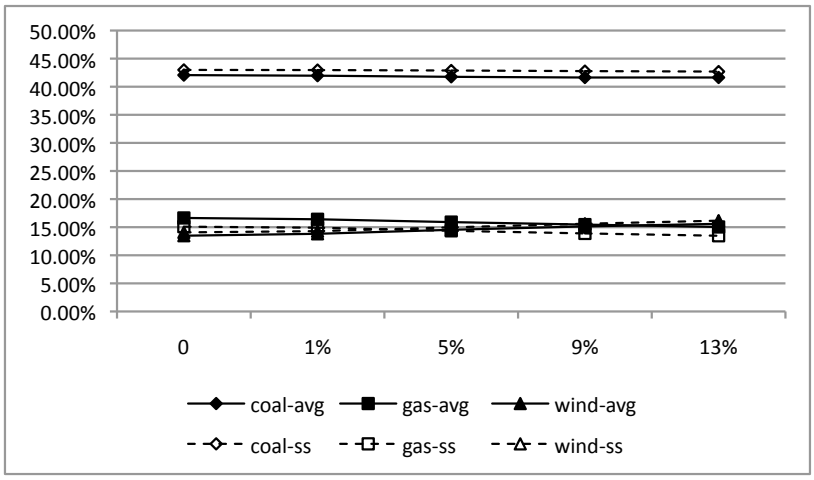
Encouraged by the results described in the previous two sections, we conducted one year period experiments combining both spatial smoothing and V2G concepts again using Las Vegas as an

example. We study the impact on the generation allocation on the different resources, by applying the two methods simultaneously as well as comparing the wind utilizations.

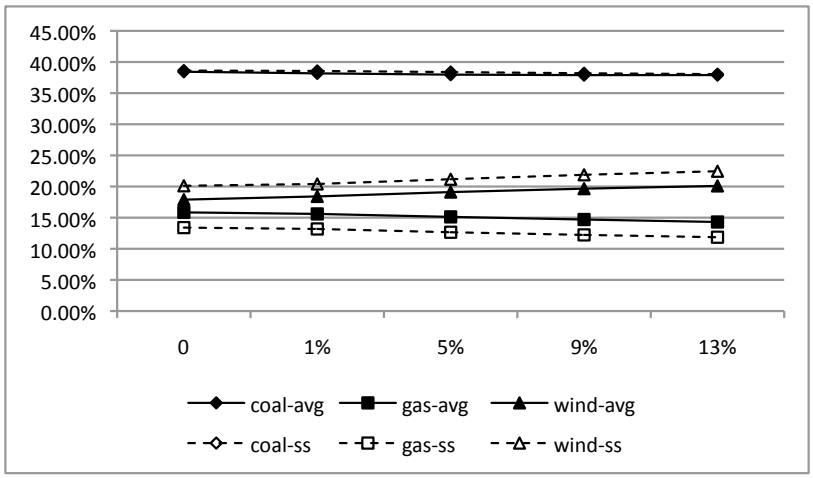
To examine the effectiveness of storage combined with spatial smoothing on generation from different resources at all four sites and including a spatial smoothing, we revisit Figure 7 and define the error bars to represent the change in value when a storage level of 13% PHEV market penetration is applied. For wind utilization and generation from wind, the storage improves both for each individual site as well as for the case of utilizing spatial smoothing by a significant margin. Similarly, the fossil-based generation is similarly reduced.

To determine the dominant impact between spatial smoothing and storage as wind penetration increases we compared the average generation values for wind, coal, and natural gas, with the equivalents using spatial smoothing. We show the results for scenarios 1, 2 and 3 in Figure 12. In Figure 12(a), there is a benefit, but it is not nearly as pronounced as with the higher levels of wind integration in Figure 12(c). In the latter scenario, wind generation approaches 30% of average load, with coal getting closer to that 30% generation mark and natural gas dropping near 10%. In all scenarios, the improvements due to storage remain fairly fixed, but the advantages from spatial smoothing appear to be increasing.

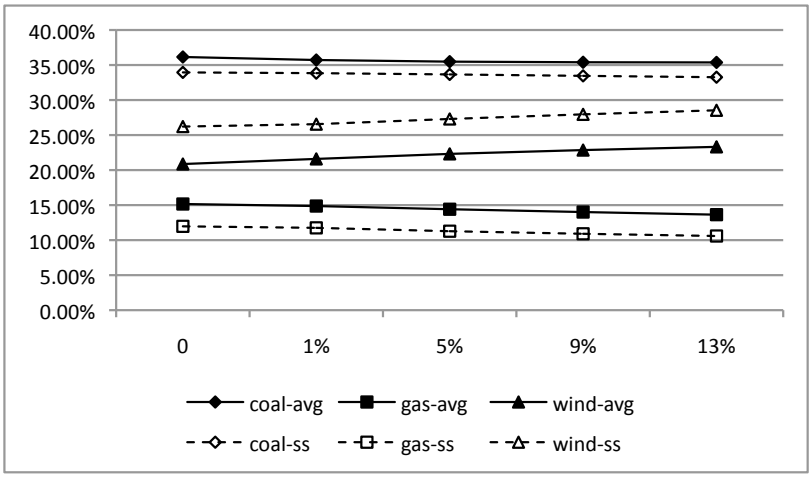
Figure 13 shows an entire result set of wind utilization in 4 researched cities, 3 different wind penetrations, and 5 different PHEV penetrations. Spatial smoothing (black line) helps improving average utilizations significantly when there is plenty of wind thus low utilization by the grid, as show in Figure 13(c). Combining spatial smoothing over distributed generations and large PHEV storage, the IGM model achieves a nearly 20% utilization improvement, ensuring reliable and efficient handling capability of the future grid.



(a) Scenario 1.

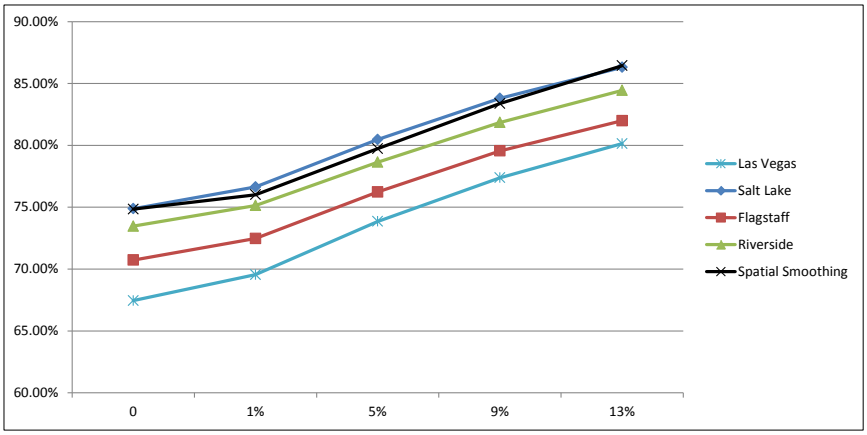


(b) Scenario 2.

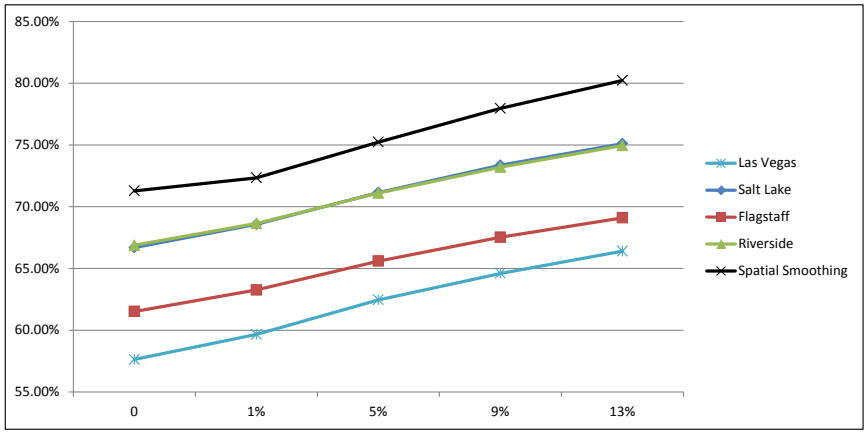


(c) Scenario 3.

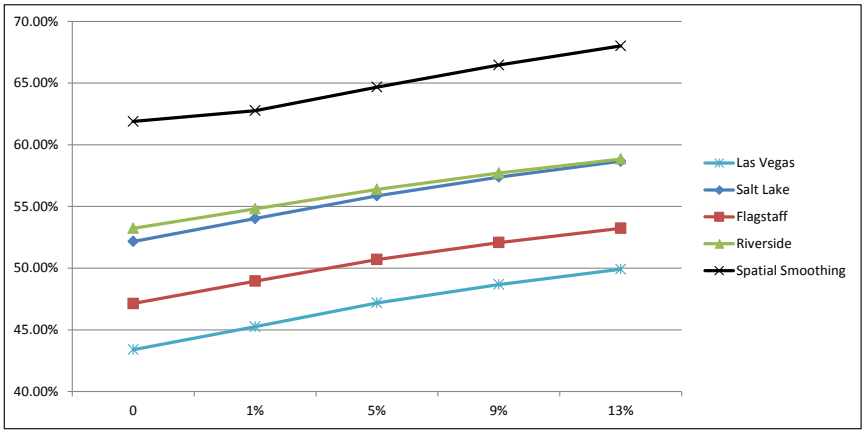
Figure 12: Improvement of spatial smoothing over average for different storage amounts.



(a) Scenario 1.



(b) Scenario 2.



(c) Scenario 3.

Figure 13: Improvements of wind utilization over different wind penetrations in 5 cities: Scenario with 40% capacity (top), with 60% capacity (middle), and with 90% capacity (bottom).

6.0 CONCLUSIONS

In this work we design an IGM model for renewable resource integration using a base of nuclear generation, load-following fossil resources and predictable massive PHEV storage to enable high levels of power from wind. In particular we examine the levels of wind integration possible using the IGM methodology, the impact of utilizing spatial smoothing technique. Additionally, we consider the impact of PHEVs as a storage resource on the grid and examine their potential contribution to furthering wind integration to the grid.

Our findings determine that spatial smoothing, while providing modest impacts within a wind farm can provide considerable benefits when used to connect various regions. Similarly, the storage provided by PHEVs, if properly harnessed, can also provide a considerable improvement to wind generation effectiveness in the grid. Additionally, both methods are orthogonal and compatible when used in concert. Our results show that the potential is there for high levels of effective wind integration into the grid even approaching 30% with these methods and that load following fossil generation, while still important, can be reduced significantly through wind and nuclear energy. Additionally, there are control methods that can effectively integrate these generation methods and optimizations together into a system.

The results of this research show great promise for the integration of renewable generation into the network. The key is that it must be possible to integrate large regions onto the same grid with a centralized IGM controller. As the results from Texas show, it is beneficial to have several turbines all producing power so that the outputs can be combined. This creates a smoothing affect which makes it easier for a centralized controller to utilize the wind power. Much better results are achieved if the Western United States are all interconnected. It is of critical importance that the interconnection be strong enough to support the flow of large amounts of power from one region to another. Effective implementation of these ideas would require the improvement of our current

distribution system. Technologies like HVDC, which greatly reduce the losses associated with the transfer of large amounts of power over long distances, could be of great use here [25]. The idea is that on days when one State does not have much wind it can use wind power produced in another State. The odds of having no wind anywhere in the Western United States are much smaller than the odds of having no wind in any particular location. So the interconnection increases reliability of the renewable resources. If many regions were all to share their wind power then each would have a much more reliable power supply. If the national grid were sufficiently efficient that power could be traded in large amounts across the entire nation. We could then imagine the output from tens of thousands of wind turbines across the country all interconnected. All of them helping with the smoothing of the others. Once again a centralized IGM controller is essential. This concept can be extended. The idea works just as well with solar power. Better yet, there could be spreading over resources if multiple stochastic resources were connected to the same grid. Similar ideas have already been explored in the European context [26].

It is also demonstrated, that decent improvement over the wind utilization can be achieved with PHEVs utilized as a storage component of the integrated generation system, which tends to get better when larger amount of PHEVs are deployed into the grid. The IGM model shows great capability in our research to handle the growing penetration of both PHEVs and wind energy, and provides optimal control strategy to maximize renewable utilization and minimize the total generation costs. An extreme scenario is that when there is always sufficient storage capacity on grid, all the spare renewable energy thus can be stored into the batteries for later use, which generates an utilization of approximately 100%. Also, with the emergence of new wind turbine technologies and more efficient power distributed systems, wind energy generation penetration into the entire electricity production is to continuously increase and estimated to reach up to 20% by 2030. Generally, higher utilization on a larger quantity of renewable power is sure to better maintain sustainability among human activities, non-renewable energy resources, and the environment.

7.0 FUTURE DIRECTIONS

In the future, additional work is needed to better quantify the benefits of the IGM concept. One interesting direction of future work is the incorporation of losses in the distribution system into the model. Accounting for distribution could make the idea of spatial smoothing less attractive since it would increase losses. It would be useful to quantify these losses for various interconnect schemes such as HVDC, which often has better efficiency for longer transmission distances [25].

While there is considerable potential to be harnessed there is a lot of work to be investigated to realize these potentials. For example, our controller requires wind speed/generation data to help make more accurate optimization decisions. Thus, it is important to connect our approach with wind prediction methods in our future work. By incorporating prediction into the optimal control model, the difficulty of control resulted from the intermittency of wind will be reduced to a large extent, decided by the accuracy and period length of prediction. Wind power will always be stochastic in nature and so better prediction means more cost efficient utilization of our resources. One way of improving prediction is spatial smoothing. The overall prediction errors could be reduced by interconnecting turbines which are distant spatially. It would be useful to quantify just how much easier prediction could become and also how this would affect the finances and feasibility.

So far, we have modelled only a centralized controller using averaged data. Another direction of future work is to set up distributed controllers and eventually integrate those parts into a whole control system on the grid. For instance, different PHEV users may cast different restrictions on the minimum power level at which they unplug the vehicles for use from the grid; spare wind power should be transmitted to places lacking supply from time to time. Those kinds of data necessarily influence the decision making of the centralized controller and therefore should be collected by large number of individual controllers dispersed throughout the country.

BIBLIOGRAPHY

[1] U.S. Department of Energy, "20% wind energy by 2030, increasing wind energy's contribution to U.S. electricity supply," July 2008, www.nrel.gov/docs/fy08osti/41869.pdf.

[2] D. G. Luenberger, *Linear and Nonlinear Programming*, 3rd ed. New York: Springer, 2007.

[3] R. O'Connor, G. Reed, Z.-H. Mao, and A. K. Jones, "Improving renewable resource utilization through integrated generation management," in *Proc. of the IEEE PES General Meeting Conference*, Minneapolis, MN, USA, July 2010.

[4] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE power & energy magazine*, pp. 52–62, 2009.

[5] R. Doherty and M. O'Malley, "A new approach to quantify reserve demand in systems with significant installed wind capacity," *IEEE Trans. Power Systems*, vol. 20, no. 2, pp. 587–595, May 2005.

[6] R. Doherty, E. Denny, and M. O'Malley, "System operation with a significant wind power penetration," in *Proc. IEEE Power Eng. Soc. General Meeting*, Denver, CO, USA, June 2004.

[7] E. Denny and M. O'Malley, "Wind generation, power system operation, and emissions reduction," *IEEE Trans. Power Systems*, vol. 21, no. 1, pp. 341–347, Feb. 2006.

[8] J. Kennedy, B. Fox, and D. J. Morrow, "Distributed generation as a balancing resource for wind generation," *IET Renew. Power Gener.*, vol. 1, no. 3, pp. 167–174, Sep. 2007.

[9] J. T. Bialasiewicz and E. Muljadi, "The wind farm aggregation impact on power quality," in *IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference*, Paris, France, Nov. 2006, pp. 4195–4200.

[10] G. Giebel, M. Nielsen, and B. Hurley, "Is least cost wind power always local in Europe? a balancing act between more transmission and lower load factor." in *Proc. of the Risø International Energy Conference*, Technical University of Denmark, May 2005.

[11] H. Wang, H. Xu, and A. K. Jones, "Crucial issues in logistic planning for electric vehicle battery application and service," in *Proceedings of the International Symposium on Traffic Information and Logistic Engineering*, 2010.

[12] IEEE Std 1547.2-2008, "IEEE application guide for IEEE std 1547, IEEE standard for interconnecting distributed resources with electric power systems," April 2009.

[13] U.S. EIA, "Average retail price of electricity to ultimate customers: Total by end-use sector," Sep. 2010, http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html.

[14] SKM, "Growth secenarios for uk renewables generation and implications for future developments and operation of electricity network," *BERR Publication URN 08/1021*, 2008.

[15] New Hampshire Electric Co-Op, "Hourly electricy consumption Aug 29-Sep 1, 1997," Aug. 1997, CVPS distribution point.

[16] U.S. EIA, "Nuclear energy overview," Aug. 2010, http://www.eia.doe.gov/emeu/mer/pdf/pages/sec8_3.pdf.

[17] ——, "Receipts and cost of fossil fuels," Sep. 2010, http://www.eia.doe.gov/cneaf/electricity/epm/chap4.pdf.

[18] P. Gipe, *Wind Energy Basics, a guide to small and micro wind systems*. Chelsea Green Publishing Company, 1999.

[19] 3TIER and National Renewable Energy Laboratory, "Wind integration datasets," http://www.nrel.gov/wind/integrationdatasets/.

[20] M. D. Rymes and D. R. Myers, "Mean preserving algorithm for smoothly interpolating averaged data," *Solar Energy*, vol. 71, no. 4, pp. 225–231, 2001.

[21] National Climatic Data Center, "One mimute wind speed data of year 2009 in las vegas," 2009, http://www.ncdc.noaa.gov/oa/ncdc.html.

[22] CITY-DATA.COM, "Population, registered vehicles, electricity usage data in las vegas," 2009, http://www.city-data.com/city/Las-Vegas-Nevada.html.

[23] J. L. SULLIVAN, I. T. SALMEEN, , and C. P. SIMON, "Phev marketplace penetration, an agent based simulation," July 2009, http://deepblue.lib.umich.edu/bitstream/2027.42/63507/1/102307.pdf.

[24] A. Y. Saber and G. K. Venayagamoorthy, "One million plug-in electric vehicles on the road by 2015," in *Proc. of the 12th International IEEE Conference on Intelligent Transportation Systems*, St. Louis, MO, USA, October 2009.

[25] G. F. Reed, B. M. Grainger, H. Bassi, E. Taylor, Z.-H. Mao, and A. K. Jones, "Analysis of high capacity power electronic technologies for integration of green energy management," in *Proc. of the IEEE PES T&D Conference*, New Orleans, LA, April 2010.

[26] G. Czisch and G. Giebel, "Realisable scenarios for a future electricity supply based 100% on renewable energies," in *Proc. Risø international energy conference*, Technical University of Denmark, May 2007, (Invited Paper).