FUNCTIONAL BENEFIT AND END-OF-LIFE ANALYSIS FOR PHOTOVOLTAIC FLUORESCENT CONCENTRATOR PROTOTYPE

by

Katherine M. McGinley

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This thesis was presented

by

Katherine M. McGinley

It was defended on

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and approved by

Marcus Zettl, GE Global Research Europe

William Slaughter, Associate Professor, Mechanical Engineering and Materials Science

Dieter Wältermann, Department of German

Thesis Director: Qing-Ming Wang, Associate Professor,

Mechanical Engineering and Materials Science

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The benefits of increased use of renewable sources such as photovoltaics to produce electricity are indisputable; however there is much work to be done in optimizing the implementation. Germany is in the forefront of research in the field of renewable energy, in large part due to governmental support in the form of the EEG, or Renewable Energy Act. My research was conducted at the GE Global Research labs in Munich, Germany, where new and innovative ways of harnessing energy from renewable sources are researched and developed.

One method of decreasing the cost per Kilowatt is the use of fluorescent concentrators, such that less silicon-based cells are needed to produce an equivalent amount of electricity. In this technology, the body of the module is formed from plastic which has been impregnated with a fluorescent dye. Incident irradiation is absorbed by the dye particles, and reemitted with a shift in wavelength. A large part of this reemitted light is conducted along the length of the collector by means of internal reflection in the plastic panel, towards small silicon cells attached to the edges of the panel. This allows the light incident on a greater surface be conducted to a much smaller area of photovoltaic material, allowing much less silicon to be used. In our prototypes, full-spectrum sunlight was absorbed and the emitted radiation was of a lower wavelength (in the red part of the visible spectrum) which is more easily absorbed by the silicon cells and converted to useful energy. This wavelength shift helped combat any losses sustained in the transmission process.

Great effort was put into the development of a suitable dye and plastic that could be used for such an application, and now the first prototypes have been in operation for a reasonable amount of time. The implementation of these prototypes, their modes of failure and degradation, and possible improvements for the system will be discussed.

Modules approximately the same size as standard, currently-available silicon-based solar panels as well as a more experimental prototype modeled on more easily installed roof tiles will be investigated for both lifecycle of the physical prototype (including degradation of the dye) and comparative performance under various real-world conditions. This will help guide the further development of the technology, so it can eventually provide a less expensive means of providing solar-derived electricity to a greater number of people with a smaller drain on natural resources

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1.0 INTRODUCTION AND PREVIOUS WORK

1.1 INTRODUCTION

1.1.1 Overview of Renewable Energy

As society advances and technology progresses, the demand for energy is growing at a rate far outstripping our ability to provide it. Currently the balance of electricity production around the world comes from non-renewable sources, whether it be coal, natural gas, fossil fuels, and occasionally nuclear. Being non-renewable, these sources of energy will presumably run out sooner or later, or be legislated into scarcity in the case of nuclear energy. Diminishing stores will lead to increased end cost for the consumer, which will lead to either an energy crisis or more optimistically, drive innovation.

While the continued ability of the world at large to supply enough power is enough of a concern, we must also take into account the greater costs associated with the demand for such huge amounts of energy. Certainly the direct cost of the fuel itself is of great concern, but so too should be the costs associated with the damage to the environment and quality of life associated with the continued unchecked use of such fuels. The sulfurous emissions from coal-fired power plants are a leading cause of acid rain, which damages both ecosystems and man-made structures. Proper disposal of nuclear waste associated with nuclear power stations has always presented a challenge, and as of yet is mainly dealt with by containing and leaving it for the next generations to manage. There are also the problems associated with active nuclear power plants- mainly the danger of a meltdown releasing radioactive material into the surrounding area, or volatile political situations where some threaten to use the radioactive material for weapons-oriented applications.

With global warming now an accepted reality, the reduction of greenhouse gas emissions, which result from the burning of fossil fuels, has been the subject of many international agreements. The Kyoto Protocol, for example, calls for the reduction of six specific greenhouse gasses including carbon dioxide, methane, and hydroflourocarbons, by up to 8% (such as in the EU) by 2008, then reinstated until 2012 (UNFCCC 5). Burning coal, a common fuel source in power generation, releases 93 kg of carbon dioxide into the atmosphere per gigajoule of energy produced (Becker 3). This has led to a sizeable rise in CO_2, from 280 ppm to 380 ppm over the course of the last 150 years due to human activity including deforestation, though mainly the burning of fossil fuels (Becker 4). This has far-reaching effects on the world at large stemming from the evident rise in temperature, ocean acidity, and water levels. Based on a 3 °C rise in global temperature, a study conducted by the National Academy of Science predicts a drop in average income by 1.7%. If a shift in precipitation, another likely scenario with the predicted climate change, is also factored into the calculations, this figure changes to a 3% decrease in average income worldwide (Nordhaus 3517).

1.1.2 Renewable Energy Sources Act (EEG)

Germany in particular is making sizeable efforts to encourage the increased ubiquity of renewable energy sources. With the Erneuerbare-Energie-Gesetz (Renewable Energy Sources Act), the country aims to increase the presence of renewable energy to 30% of the market by the year 2020 by offering guaranteed incentives over the course of twenty years to feed into the grid. By the end of 2009 Germany was able to fulfill the benchmark of a 20% reduction of carbon emissions, back to the levels present in 1990, set forth by the Kyoto Protocol. As the infrastructure and methods of production become more supportive to the industry, the tariffs will be slowly lowered at a rate of 8%-10% in the year 2010 and 9% thereafter until a self-sustaining industry remains (EEG 6). For an installation on open land, the tariff paid in 2009 is 31.94 Euro-cents per Kilowatt-hour, and for building-mounted systems the rates range from 43.01 Euro-cents per Kilowatt-hour for the first 30 Kilowatts to 33 Euro-cents per Kilowatt-hour after a megawatt of production capacity (EEG 10).

While the initial cost of photovoltaics is undeniably high in the current market, the benefits of the initial investment can be huge if used correctly. Many areas have a high enough average irradiance to generate a significant amount of power using even a modest amount of area. In places such as Bavaria, with both a sizeable amount of average irradiation and government support, the time to recoup the initial cost of the system can be shrunk even further.

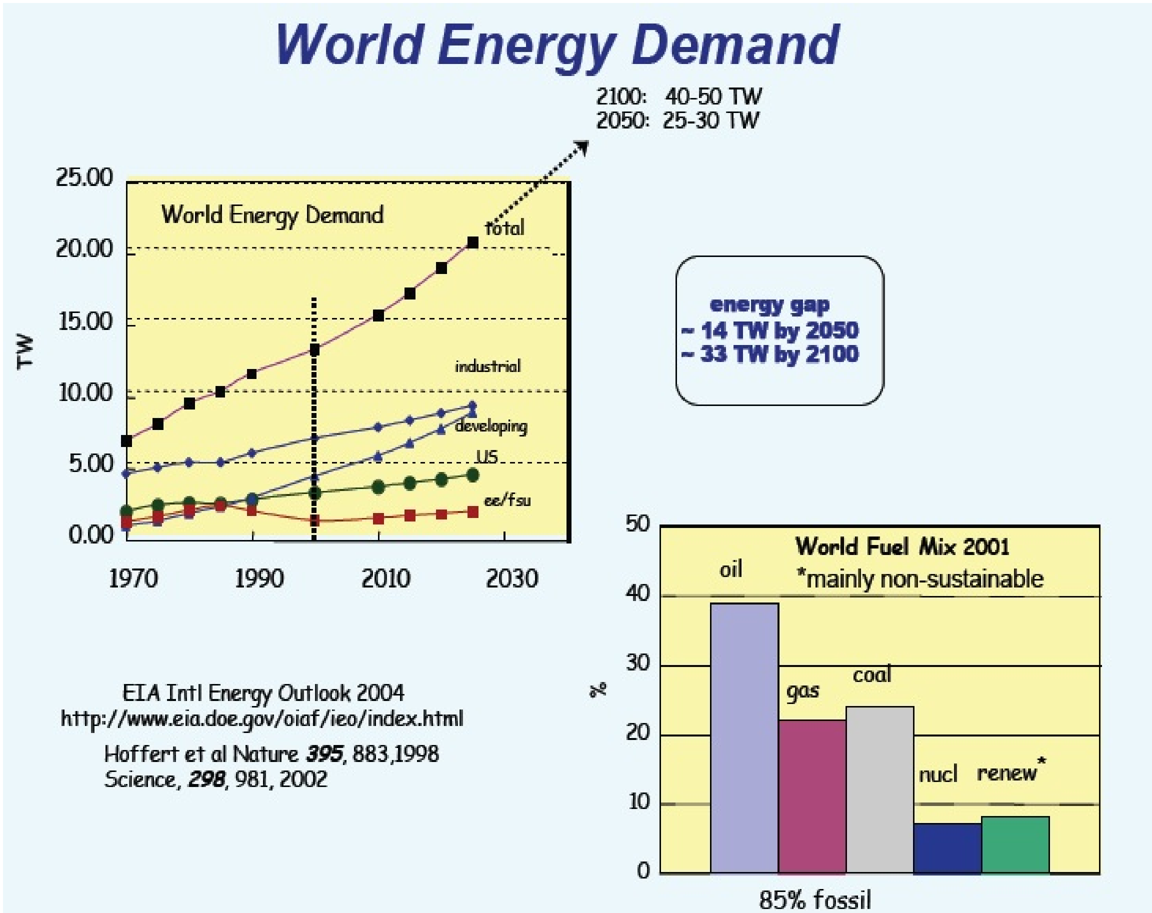

Figure 1.1 Illustrating rising world energy demand, and current sources (Graetzel)

1.1.3 GE Global Research Europe

I had the opportunity to hold a 6-month internship, or in German a Praktikumsemester, at the GE Global Research Center in Garching, on the outskirts of Munich, Germany. The facility is state-of-the-art, and houses one of several centers for research and development of new and existing technologies for GE, one of the biggest companies in the world. The Munich facility houses labs for many different branches of GE, whose duties range from developing windmill turbines, to new types of MRI, to housing one of the largest indoor solar simulators in the world. Divided into specialized teams and labs, we worked in conjunction with companion facilities in upstate

New York, China, and India, as well as collaborating with scientists from all over the world. My facility alone employed scientists from more than 14 different countries, and my lab represented at least seven.

The experience has been nothing but positive. It allowed me not only the opportunity to learn a lot about an emerging field and gain practical experience both in the areas of solar power generation and testing, but also of working in a research, not profit-driven, environment. I worked side by side with scientists on a daily basis, which allowed me to see a broader perspective and range of methods than I would have anywhere else. I am glad I had this unique opportunity to see such a burgeoning field from such an international perspective.

1.1.4 Objective of the Polar Bear Project

Given the rising energy costs and consumer awareness of environmental impact, a substantial market exists for an affordable provider of accessible solar energy technology. GE started to pursue this with the project called "Polar Bear"- a fluorescent solar concentrator that could undercut the cost associated with current flat-panel technology and reduce the amount of material needed for solar energy production, while increasing consumer flexibility. The current market is fairly divided (Rice 16), with several providers offering similar options, though the technologies range from monocrystalline to thin-film. A few more exotic technologies are available, but silicon continues to dominate the market.

GE also holds several advantages against more specialized companies which might only produce solar panels. With brand recognition and trust already in place, not to mention existing relations with distributors and contractors, they would be in a position to better introduce a new product to the market with minimized risk (Rice 17). GE is in a position to gain funding from government sources investigating renewable energy technologies, in this case the Bavarian Wirtschaftsministerium (Mayer, Stromberger 5) They also currently produce other components of the complete solar-energy system, such as the inverter, which could be packaged with the modules as a complete set for both ease of installation for the consumer and a better market share for GE (Rice 16). Producing the entire solar-energy installation or conversion package would also take advantage of the several branches of GE that could contribute to a single project, including consumer products, plastics, and energy, rather than having to outsource for components as competitors might have to do (Rice 17).

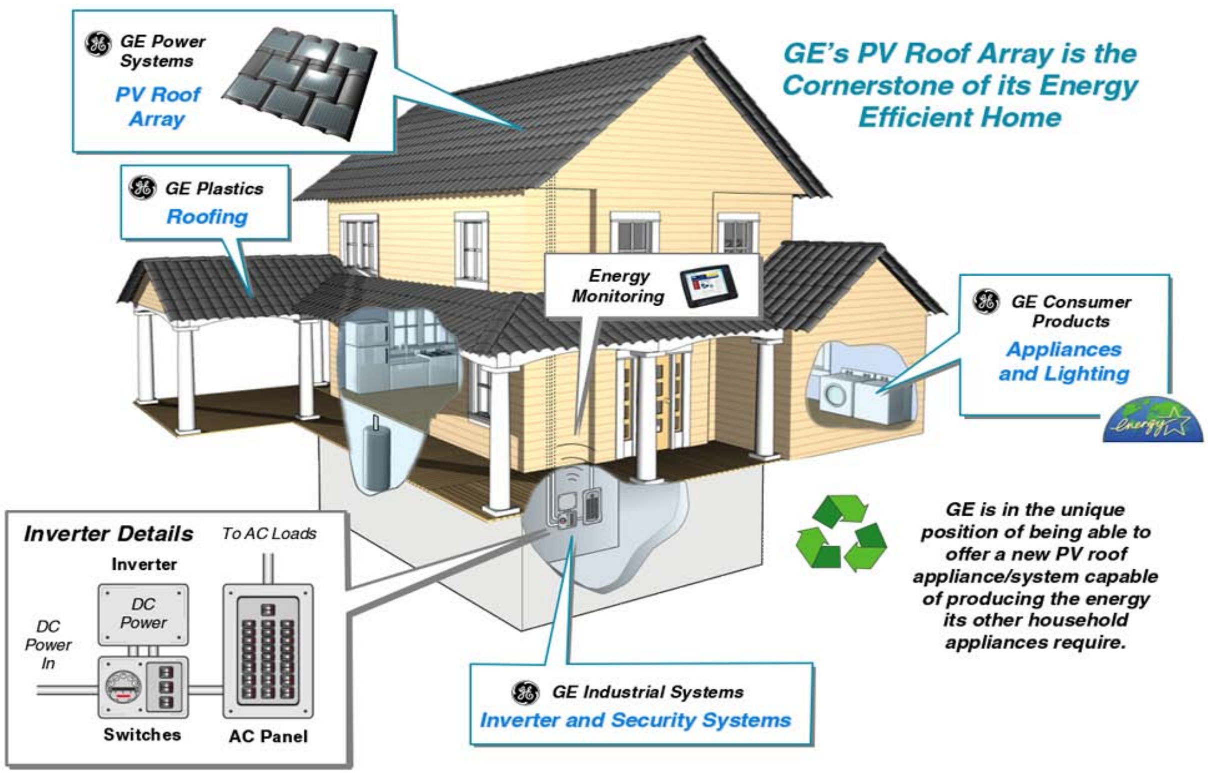

Figure 1.2 Example of integrated GE whole-home system (Rice 24)

If GE were able to develop and produce a fluorescent concentrator system for the personal-home market, they could presumably distribute it at a lesser cost than current roof-mounted silicon flat-panel system. This was a primary motivation for the Polar Bear project as it took shape - at the beginning the model was to encompass solar-thermal elements, so the concentrator system would allow a minimum of heat around the solar cells, but allow the collection of heat in another part of the cell. This took on the name Polar Bear because the hairs in the bear's white coat act on a similar principle as fluorescent concentrators, directing light towards the animal's dark skin to keep it warm. Later on in the project, the fluorescent collector component was focused on more specifically, though a solar-thermal element could still be developed in the future.

With the rise in consumer concern and government funding earlier in the decade, GE saw an opportunity to develop technology in anticipation of a rising consumer demand. Costs for the materials were consistently decreasing, government subsidies were strong, and all signs pointed to an expanding market (GE Global Research, "CEO Program Presentation" 5). From a production and sales standpoint, in 2003 the cost per Watt output of photovoltaic cell production was $2.40, but the projected cost of the Polar Bear project module was closer to $1.70 per Watt output (Wild 25). Even if sold at a discount to the consumer, this allows for an increase in profit to the company. From the consumer's point of view, the cost of converting to solar drops as the subsidies rise, and with the decreased initial investment, financing, and feed-in tariffs in places such as Germany and California, the return could even outweigh the monthly cost of the financing (GE Global Research, "CEO Program Presentation" 25).

1.2 COMPONENT OVERVIEW

1.2.1 Overview of Photovoltaic Power Generation

The functional element in most contemporary solar panels is silicon. This can be monocrystalline, where a single large crystal is induced to grow and is sliced into wafers for cells, polycrystalline, a less expensive option, or amorphous, and the least expensive of the common silicon options. Monocrystalline cells generally produce the best results, but are much more expensive than other options.

When a photon from a light source with a suitable range of wavelengths with sufficient energy strikes the silicon, some electron-hole pairs are created by valence electrons leaving the valence band. If the photon is absorbed and the energy is greater than the semiconductor bandgap energy, the excess will be converted into heat, driving down the overall performance of the solar cell.

This leaves a place for another electron in the conduction band to take its place, and the process continues, creating a voltage and current. In direct bandgap materials, only the energy (rather than the energy and momentum) of the photon is needed to generate an electron-hole pair (EHP), which makes cells made from these materials able to be much thinner than indirect-bandgap materials that also require momentum transfer from the photon (Messenger, Ventre 347). Each of the semiconductors used for this purpose have an inherent quantity of EHPs due to the thermal energy available being over 0 °K, and each of them have a certain capacity for EHP mobility, also dependant on temperature. This does not become particularly useful until even greater numbers of EHPs are generated by the application of sunlight, and can be induced into doing work rather than moving around with random thermally-generated velocity. When placed in an electric field, a drift velocity is superimposed on the existing thermal velocity, and can start to be put to use.

When materials are purposefully doped in order to be more favorable to electron or hole generation, and then layered with the opposite type of impurity, an opposite-direction diffusion current can be added to the drift current due to the higher concentration of electrons or holes in different areas (Messenger, Ventre 349). Now there are a number of thermally-generated and photo-generated electron-hole pairs moving both randomly due to thermal energy and in particular directions in drift and diffusion currents. These EHPs have a generally limited lifetime before they recombine and lose their potential to do work, and the goal is to generate a useful current and voltage in the process of their recombination through an electrical terminal rather than across the p-n junction (Messenger, Ventre 339).

If the charge carriers are generated within this distance from the junction, it is more probable that they will be able to be put to work rather than recombining before reaching the junction and no longer being available for conduction. In order to maximize the useful potential of the system, the junction should be fairly close to a diffusion-length from the surface such that most photo-generated EHPs can reach the junction before recombining.

The resulting voltage and current is then modified to grid-acceptable parameters by one or several inverters, depending on where DC and AC current is desired, and then fed into the grid. In Germany, it is required for this power to be accepted by the grid and, pending quality and compliance inspection, monetarily compensated at the previously set forth rate. (EEG 3).

Heat, while slightly increasing the current, greatly decreases the voltage and adversely affects the materials, which can shorten the overall lifetime of the module. When taking into account that both energy and momentum transport take place, the efficiency of the process can be optimized through consideration of the available light and choice of the semiconductor material. Based upon the proportion of photons that contain enough energy to be converted into electron-hole pairs for a given band gap, the limiting efficiency hovers around 40%, which can be raised to around 86% if multijunction cells which layer different semiconductors are used to capture a broader part of the spectrum (Luque, Andreev 12).

1.2.2 Maximizing Yield

If the yield of the system is dependent on: quantity and quality of irradiation, ability of the solar collectors to come in contact with the maximum amount of solar irradiation, efficiency of the collectors in converting the energy in the solar irradiation to electricity, and losses in the system after conversion, it makes sense to optimize any of these variables in order to maximize yield.

Quality and quantity of sunlight can be better guaranteed by choosing a particularly sunny location like Sicily or Spain. Places with the most sunlight are not always going to have equally hospitable political climates though, and may be too far away from the desired customer to make sense. Covering Africa or the Middle East with solar panels might make sense in terms of irradiation, but not convenience or politics.

Efficiency of the solar collectors is always being improved through ongoing research and development of the panels, and some materials are known for being more efficient than others, particularly in the distinction between direct and indirect bandgap materials. Different materials can also be stacked to make use of more of the available spectrum in what are termed "multijunction" cells. Temperature and environment can also affect the performance of a solar cell-- an excess of heat significantly decreases a module's efficiency. This is another reason why blanketing the Sahara in silicon would not necessarily solve the energy crisis.

System losses can be minimized through the choice of inverter and minimizing cabling, and connecting to an appropriate grid or storage system. If cabling losses were not an issue, one could theoretically generate solar energy in China while the US sleeps, and the other way around, but as of yet there is no way to conduct or even store this much energy for this to be feasible.

This leaves maximizing the available collection area presented to the sun. If conventional solar panels are used to convert the energy in the irradiation of the sun directly to electricity, then only the irradiation normal to the area of the plane of the solar panel is utilized. This direct irradiation is the greatest source of energy to the system, though of course diffuse irradiation contributes some measure to the power generation as well. By increasing the area normal to the direct irradiation, more of it can be converted into electricity, though with traditional flat-panel collectors generally made of silicon, cost soon becomes an issue.

One way to solve this problem is to use mirrors to redirect the sunlight incident on a certain plane to a point or line, where the solar panels are located, reducing the needed amount of expensive semiconductor for the same amount of generated electricity (Becker 2008). This method encourages the use of even more efficient modules because temperature quickly becomes an issue. Reduced size also makes such an investment more affordable by comparison. In the end, the concentrator will have less than 100% efficiency, as will the photovoltaic unit. The precision mirrors, efficient modules, and necessary tracking systems do imply a certain financial investment, but at the end the cost per Kilowatt-hour of produced electricity can be greatly reduced from that of conventional solar cells.

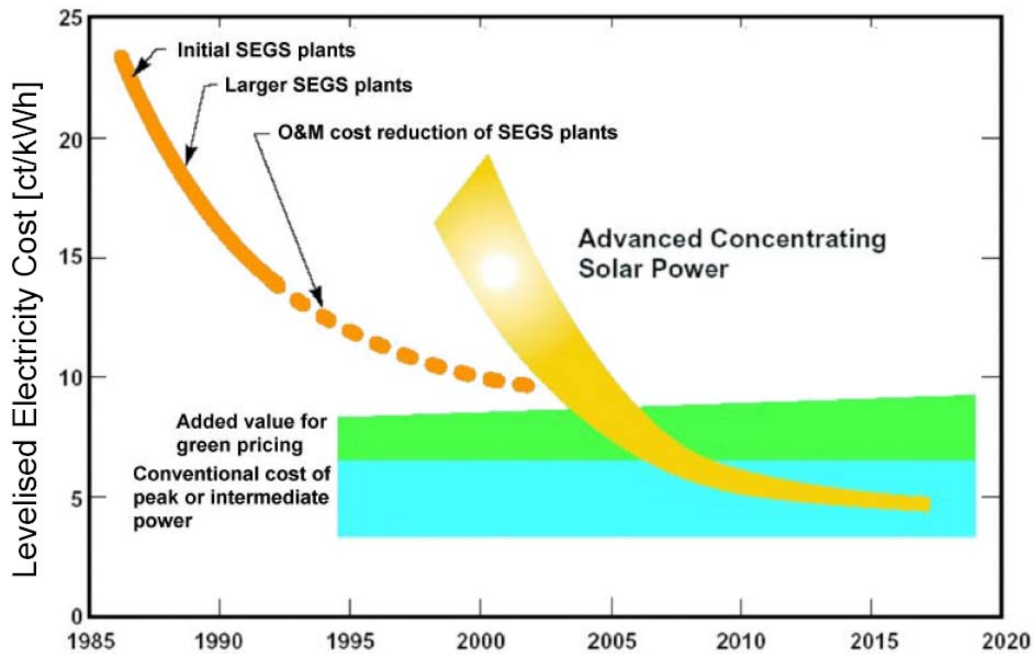

Figure 1.3 Predicted cost per kilowatt-hour with concentrating photovoltaics

(Mayer, Zettl, Frey, Stern, Ast 20)

1.2.3 Fluorescent Concentrators

Another way of concentrating incident sunlight to a smaller area of solar panels is through the use of fluorescent concentrators. These use a sheet of glass or plastic, either coated or impregnated with a fluorescent dye, to collect and redirect the irradiation. First, the incident sunlight strikes the (in our case, polycarbonate impregnated with dye) collector. Some measure of it is reflected at the surface, another part passes through the other side, but a good amount is absorbed by the fluorescent dye. This energy is then reemitted with a matching profile, though shifted wavelength, and transmitted with minimal losses to the edges of the material. Some of the approximately spherically emitted light of course is lost from either side of the sheet dependant on angle of incidence, but the rest is conducted via internal reflection towards the edges, where the solar panel stripes are affixed. Because of the transparent nature of the collector, direct sunlight has a greater tendency to pass through and not generate as much useful remittance. Diffuse sunlight however, which conventional collectors cannot make great use of, works particularly well with this system-- letting it fill a price, technology, and available sunlight niche.

A fluorescent collector also has several functional advantages over more conventional solar cells. Heat decreases the efficiency of the photovoltaic conversion, but in a fluorescent collector, the buildup of heat in the cell is much less than if the entire surface of the solar cell were presented to the sun. If the dye is chosen correctly, it should have a broad absorption range and reemit the light at a wavelength above the bandgap of the solar cell. In concentrating the light incident on a much larger area onto a much smaller area of photovoltaic cell, high efficiency cells can be used. Another benefit is that this type of concentrator does not require a tracking system, unlike a parabolic mirror system (Richards, Shalav, Corkish 1)**.**

The limiting factors of this technology come from the efficiencies of each part of the conversion process. Though the proposed possible efficiency reached 9% (Bachtelder 10), the highest recorded combined efficiency of the collector was only 4.5% through the 80s and 90s. When the light enters the collectors, part of it passes through the collector, and only part of the spectrum is in the absorption band of the dye. Some of this is reabsorbed by another dye molecule, and so subjected to another round of losses, though this phenomenon is exhausted only after a couple of centimeters (Thomas, Drake, Leisiecki 1). After this, part of the reemitted light falls within the escape cone-- the typically 42 degrees from vertical before total internal reflection directs the light to the edges. This depends on the refraction index of the matrix, usually assumed to be 1.5. Even that is not quite total internal reflection-- part of the light is lost due to necessarily imperfect surface conditions of the matrix. Another part is lost to absorption and conversion to heat in a not entirely transparent matrix.

Even once the remaining light reaches the photovoltaic cell, only part of it is in the absorption range. To some extent, these parameters can be optimized to reduce losses, which the Polar Bear project set out to do (Richards, Shalav, Corkish1)**.**

In general, the function of the concentrator can be classified into seven stages of the power-producing process: entrance, absorption, emittance, reabsorption, transportation, optical interface crossing, and electricity production. The light enters the concentrator in the first stage, which is influenced by the surface conditions of the concentrator. In the second stage, the photons are absorbed by the dye suspended in the matrix, and reemitted at a lower wavelength due to the Stokes shift characteristic to the dye used. The wavelength of light emitted should be tailored to match the absorption spectrum of the solar cells to maximize the efficiency of the photovoltaic process by selecting a fluorescent dye and solar cell that are well matched. The light is emitted spherically from the dye molecules, leading to some of the emitted light being lost out of the top of the concentrator. In traveling toward the solar cell, some of the emitted light is reabsorbed by other dye molecules in its path. When it is reemitted the process is not entirely efficient, so each time the light is reabsorbed it represents a loss in the system. Reemittance also subjects the light to another round of effects from the loss cone when spherically emitted (Rowan, Wilson, Richards 4). Changing the dye density to minimize this effect can optimize this process. After being reemitted from the dye molecule, the photon must travel to the solar cell in the transportation phase. The optical clarity of the matrix plays a large role in minimizing losses in this phase, as does the surface condition of the matrix, which contributes to the total internal reflection. The solar cells are attached to the concentrator with a material that has a similar refractive index to the matrix of the concentrator so that total internal reflection does not occur at the optical interface between the cell and the concentrator. Finally, the photon reaches the photovoltaic cell. The efficiency of the electricity production phase is dictated by the efficiency of the solar cell, though it is generally higher than the same solar cells in a more standard installation because of the lower running temperatures in the concentrator and optimized wavelength of the reemitted light (Pohl 31)

A similar method of creating the concentrator is to coat a clear material with a thin layer of photon-doped film. This allows for less interference in the transport stage, but greater loss when the light is emitted. Another obstacle to this method is the ease of production: plate glass can be coated with this film, but even then it adds another step to the production process requiring specialized equipment, and can be difficult to ensure a durable, robust product. Mixing the dye directly into a polycarbonate matrix ensures that the fluorescent capability will not be compromised in instances of coatings flaking or chipping off, and the polycarbonate can be molded to specification, making it a much more versatile option for creating the concentrator than plate glass (Grande, Moss, Milward, Saich 1).

1.3 THE POLAR BEAR PROJECT

1.3.1 GE Prototype

At GE we had two particular prototypes using the fluorescent collector technology-- one the size of an average flat-panel collector, and another in the shape of individual roof tiles, with which I worked more closely. The roof tile prototype had been designed to give the consumer an easier way to break into the solar market without needing to fit roofs with extra racks and costly panels-

- these could be installed in the same way as a regular roof by a roofer with minimal special training, and the modular nature makes the cost easily scalable to the consumer's needs.

In conventional solar panels, the area exposed to the sun is the silicon, which is fairly expensive in quantity. The goal of using a fluorescent concentrator in the Polar Bear project is to reduce the amount of silicon needed to produce an amount of electricity. The material used for the concentrator is not only more cost-effective than silicon, but at an estimated 33.60 Euro per square meter, is only roughly twice as expensive as plain, clay roof tiles (GE Global Research, "Comparison Ziegel").

Being developed at GE, the project was designed with the Six Sigma measure of quality control in mind. In short, it is a method to ensure consistency, repeatability, and quality in all the products developed by the company. It aims to minimize the risk to the company by designing to a standard of less than 3.4 errors per million samples (Pohl 31).

1.3.2 Development of the Matrix Material

In order to fulfill the purpose of a fluorescent collector, the matrix used to suspend the fluorescent dye should optimize several different properties. First, the matrix should have a very high optical transmission rate. Both glasses and plastics work well for this, but glass has generally better surface conditions for total internal reflection. Inorganic dyes however, which generally have wider absorption ranges, cannot be deposited in glass (Richards, Shalav, Corkish 2), as they decompose at the high temperatures needed to incorporate the dyes into the melted glass. Once the light is absorbed by the dye and reemitted, the goal is for as much of it as possible to be directed toward the solar cells on the edges, and a material with high optical clarity makes this possible. Next, in order to have as long a lifetime as possible, the material used for the matrix should not degrade due to the UV radiation it will be exposed to in the sunlight. It should be nonreactive in general-- with the dye, the material used to affix the solar panel strips, fittings, or conditions that may predictably arise in outdoor use such as rain and snow. Part of the appeal of a fluorescent collector as opposed to a mirror-collector is the high degree of flexibility one has when designing the shape of the collector. For this reason, an easily formed and treated material is preferred for the matrix.

In this project, we had the advantage of having access to the GE Plastics division, which provided the design team with a material that fit the needs of the fluorescent collector. Lexan, a clear polycarbonate manufactured by GE Plastics, not only met these criteria, but had additional positive traits such as being shatterproof (Wiersma 32).

1.3.3 Development of the Dye

As mentioned before, the purpose of the fluorescent dye in this type of concentrator is to absorb and then reemit photons at a matching profile, but different wavelength. First, the desired absorption and emittance spectrum had to be specified for our purposes, and then a dye either selected from existing stock or developed specifically for the project. The ideal absorption spectrum would take advantage of the available sunlight in our area, starting around 600 nm, and then down shift it to the ideal emittance spectrum, around 900 nm, a wavelength most compatible with the solar cells used. The dye used would ideally avoid much overlap between the absorption and emittance spectrums and have a high quantum efficiency in order to minimize losses from reabsorption. It should also be resistant to degradation in the presence of ultraviolet radiation and high temperatures, as could be expected in daily use in sunlight and in the presence of foreseeable inclusions and flaws in the matrix layer (GE Global Research, “The Desired Dye”

1). Options exist both in organic and inorganic dyes, with newer inorganic dyes including quantum dots and rare earth metals such as neodymium providing the desired wide absorption bands. These relatively newly developed dyes need to be present in fairly high concentrations though, thereby increasing the cost. They are also only widely commercially available at low quantum efficiencies of around 10%, and lack long-term stability (Rowan, Wilson, Richards 3).

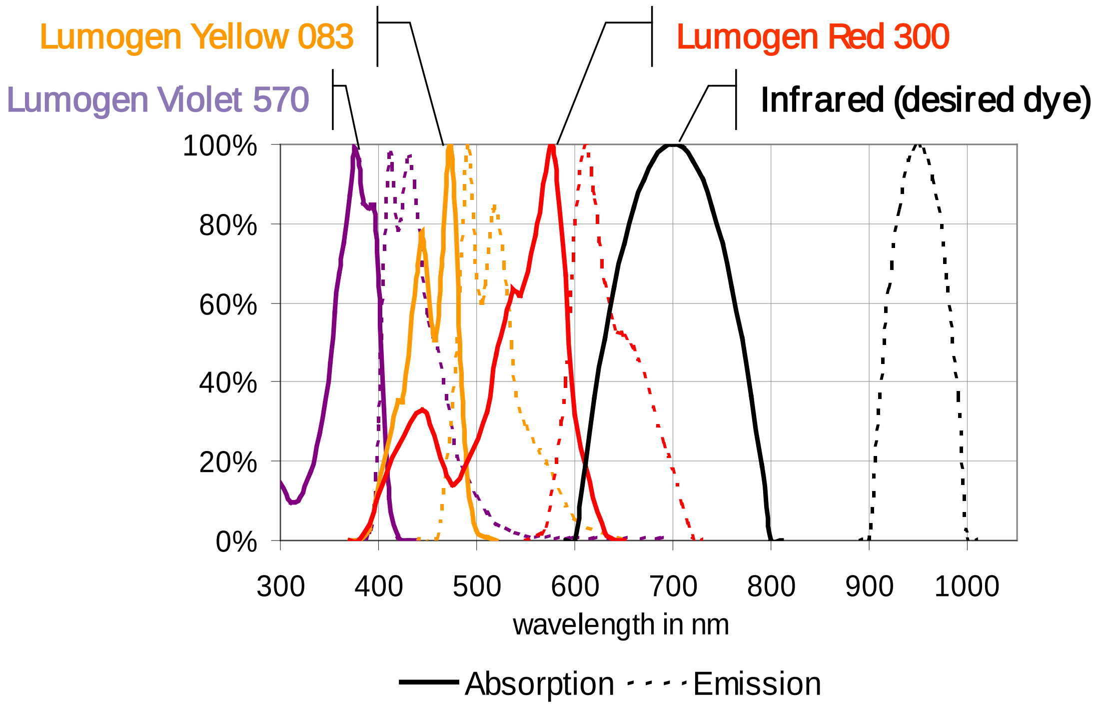

Figure 1.4 Absorption and emittance characteristics of existing and desired dye (GE Global Research, "The Desired Dye" 1)

Our particular dye was studied and selected in conjunction with the Technical University of Munich (TUM), and produced by BASF. Called Lumogen Red, it was chosen after testing several other dyes because it had a relatively large absorption range and emitted in the red and infrared range of the spectrum. Previous research had also already shown the Lumogen F series to have comparatively low rates of degradation in UV light over time (Wilson, Richards 3). Because this range of light best matched the bandgap of our solar cells, it was converted into usable electricity most easily, boosting the efficiency of the cells compared to performance in unchanged sunlight. The possibility still exists to combine the Lumogen Red layer with other layers of concentrator using a different dye in order to capture a greater range of available light, but for the prototype, only the best-suited single dye to the purpose was used. If this is decided upon later, a similar process could be used to create the subsequent layers as was used in the final design of the Lumogen Red layer.

Once the dye was chosen, the means by which it and the matrix were combined needed to be decided upon. Either the dye would be deposited in a layer on top of the transparent matrix, or mixed into the matrix itself. Methods of depositing one or several layers of dye on a transparent matrix, as well as a dye-doped matrix were tested, and many showed positive results (Stern, Ruth, Mayer 12)**.** For the purposes of the prototype however, it was decided to use only a dye-doped matrix due to difficulties in producing a durable sample with dye coatings that did not flake or crack (Stern, Ruth, Mayer 12).

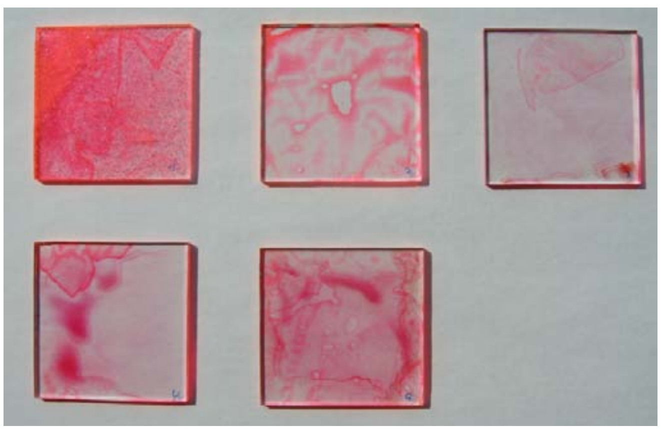

Figure 1.5 Wetting errors in applying coatings (Stern, Ruth, Mayer 3)

Figure 1.6 Coating cracking and flaking, difficulty applying coatings (Stern, Ruth, Mayer 3)

Once the dye and method of integrating the dye and matrix were chosen, sources of losses were analyzed to best tailor the concentration of dye and quantify how much of the irradiation not targeted by the specific dye was leading to possible losses in the system.

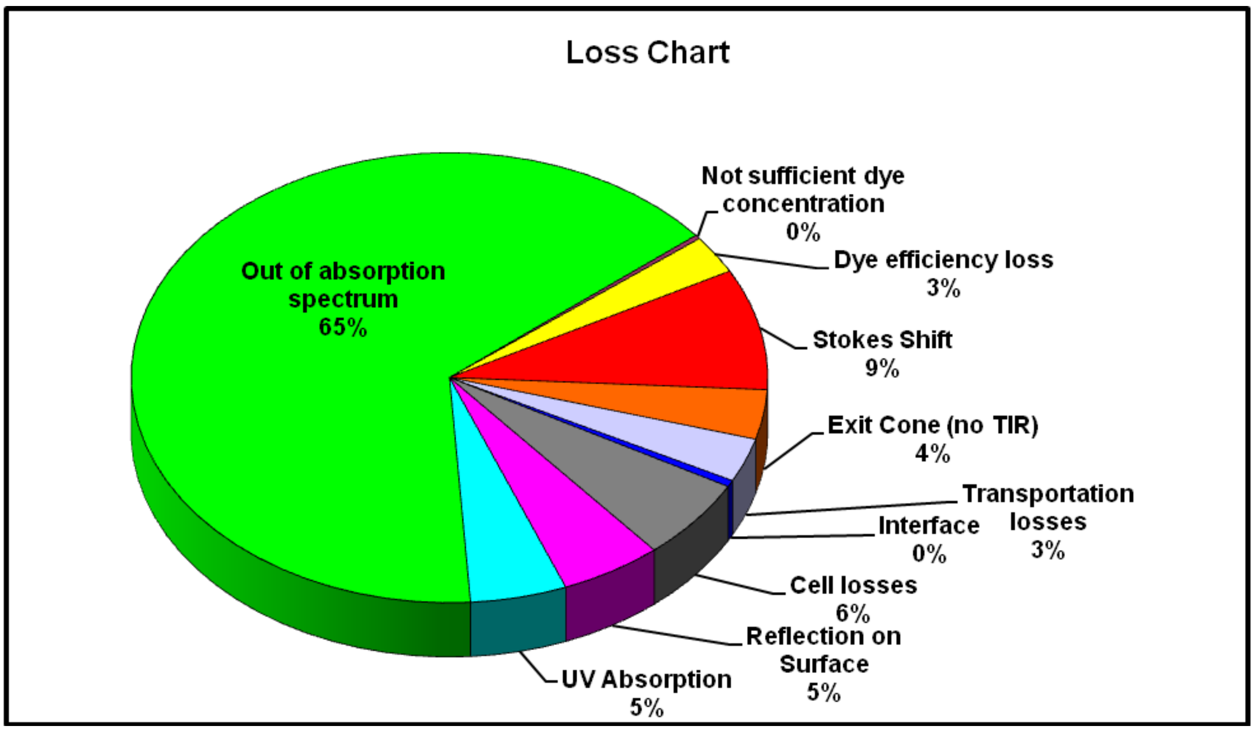

Figure 1.7 Losses in the fluorescent concentrator system (GE Global Research, “Loss Chart”)

1.3.4 Preparing the Solar Cells

Not only was developing the matrix and dye a challenge, but so was preparing the solar cells for use in a concentrator of this type. Solar cells are composed mainly of very thin slices of silicon, and as such are very brittle and fragile. Papers have been devoted to the subject of the treatment of solar cells, and have concluded that water jet guided laser cutting is a good way to slice solar cells in order to avoid unnecessary shattering or heat damage. (Heikenwälder, Matthees, Richerzhagen, Seim 2).

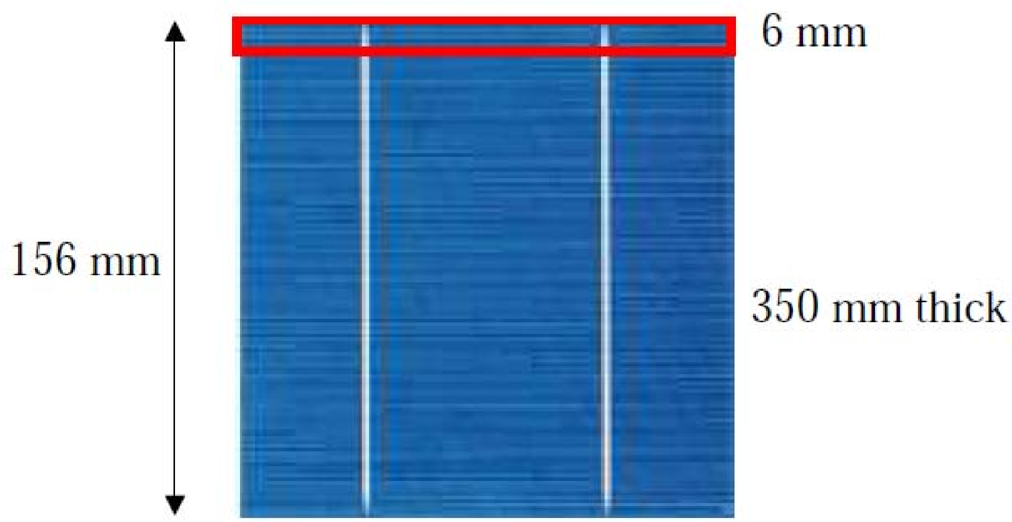

Figure 1.8 Cutting the solar cell. (GE Global Research, "Solar Zellen Streifen")

1.3.5 Creating the Roof Tile Prototype

Because of the material used for the matrix for the fluorescent concentrator, it can be formed to fit any number of applications or locations. One idea to bring the concept of a concentrating system to the consumer market and use already available space was to make a roof tile that also produced electricity. Some research in the past has suggested that a hexagonal plate provides the best configuration of solar cells and concentrator to maximize efficiency (Bachtelder 17) but because ease of use and installation is a factor in the roof-tile design, it was decided to use a more standard size and shape that could be easily integrated with existing roofing materials. The shape of the tile only needed to not inhibit the reemitted light from reaching the solar cells at the edges. A ray-tracing model was created to predict whether the tile shape used was suitable for the purpose. This was done for both a straight sample and the traditional German “Harzer Pfanne” style roof tile, where the straight sample was predicted to have 7.24% optical efficiency, and the roof tile 5.62% (Pohl 77).

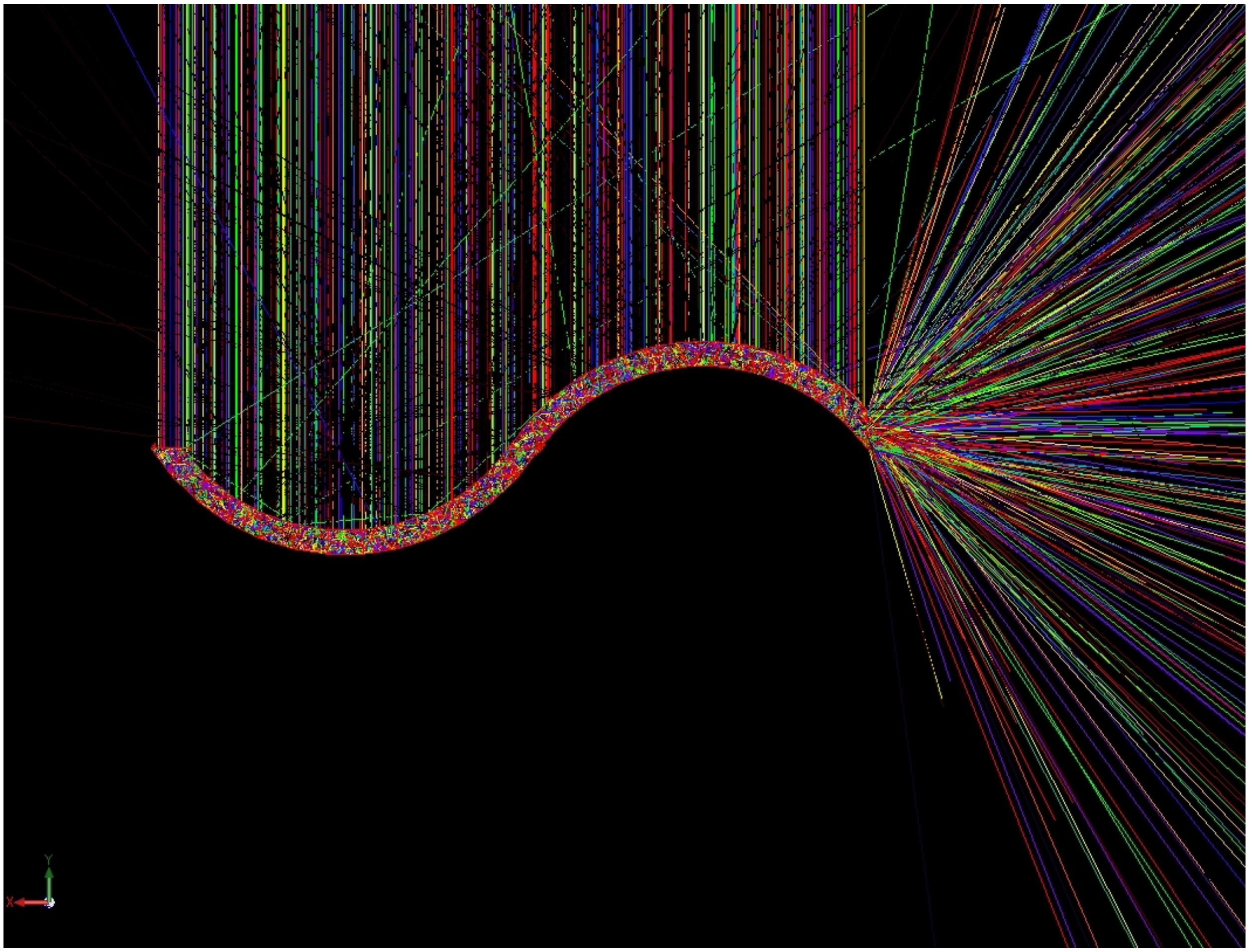

Figure 1.9 Ray tracing prediction of external and internal reflection in Harzer Pfanne curved tile (GE Global Research, “Tile 1 Reflection”)

The roof-tile system prototype was designed to last at most a couple of months outside in the elements, though it was left out for about a year to get a better idea of how the particular assembly aged. I deconstructed it and brought it into the lab in order to analyze the durability of the installation, and resilience of the materials, and the output data from our tests.

1.3.6 Construction and Installation

For both prototypes, the size and shape of the collector was determined-- either the shape as a roof tile or a module approximately the dimensions of a more standard flat-panel module-- and molded out of the dye-impregnated Lexan polycarbonate. The solar cells were cut and affixed to the two light-transmitting edges of each tile with Loc-Tite, a commercially available glue with an appropriate refraction index and weather resistance. Care was taken to avoid air bubbles and fully encase the modules in the material to avoid as much exposure to the elements as possible. The solar cells were connected in series with solder, and then electrical leads were soldered to the end cells to provide a means by which to connect adjoining tiles. The tiles were arranged in a four-by-four square, with the edges of the tiles connected in series for each vertical column. This resulted in four connections of eight edges of a tile, and each edge consisted of three slices of a solar cell. Holes were drilled into the matrix, and the tiles were attached to the roof of the bicycle parking of the research center with wood screws.

The larger prototype was mounted to the outdoor test bench at a stationary angle of 60 degrees to the horizontal with standard mounting hardware. It was placed next to the Sanyo monocrystalline module that served as a benchmark for comparison.

2.0 END-OF-LIFE ANALYSIS AND RESULTS

2.1 ROOF-TILE PROTOTYPE

2.1.1 After one year

The Polar Bear fluorescent collector concept was applied to the two separate prototypes, which were manufactured to different specifications. The roof tiles were meant to sustain normal wear and tear from outdoor installation for about a month, but the flat-panel model for much longer.

Even upon cursory investigation it was apparent that the system was not in the best shape-- it was dirty, many of the connecting wires were disconnected and broken away from the tiles, and some of the solar panel strips had peeled away from the tiles and in some cases chipped off completely. Many more of the electrical leads broke off in disassembling the array, and even more with normal handling in the lab, so it is safe to say that the particular connection method for these was a weak point in the construction of the prototype over time. Another was the connection between the solar strips and the fluorescent plastic-- solar cells have a much better conversion rate of the light when there was no air gap between the plastic and the cell, so rigid glue of a particular refraction index was used to attach and seal the solar cells to the roof tiles. Unfortunately, with time and exposure, this glue became brittle and when some of the connections between the solar cells experienced some corrosion, the glue cracked and flaked off.

This exposed the solar cells which in turn sustained damage, damaging the function of the entire system, showing that there is still much work to be done in developing the technology before it is stable and ready for market.

The roof-tile prototype consisted of 16 tiles, with cut solar cells affixed to two of the four sides of the tile. Each side consisted of four slices of solar panel soldered together in series. Arranged in a 4x4 square with vertically overlapping rows, the vertical rows were connected in series up one side and down the other to form four strings of eight sides, or 32 slivers of solar panel apiece. This many connections allowed for several sites for mechanical failure.

Figure 2.1 Installation configuration before deconstruction

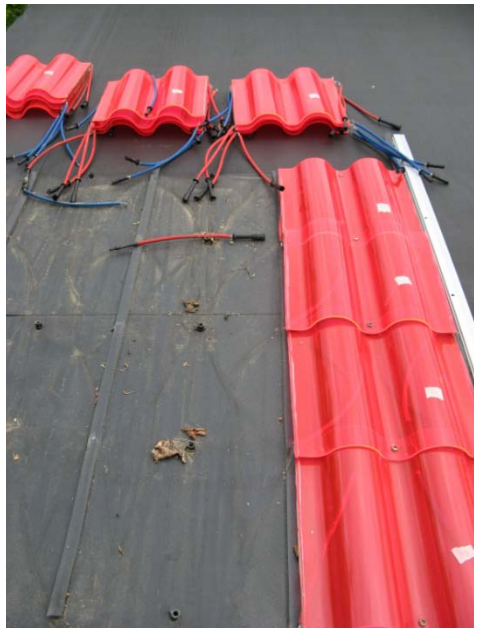

Figure 2.2 Installation partially deconstructed

2.1.2 Deconstructing the installation

The roof-tile installation was deconstructed by hand and care was taken to ensure that the tiles sustained as little damage as possible, though many of the connections to the electrical leads were fragile and damaged. Several broke off during the deconstruction, as did several more during the testing in the lab, which served to show how delicate the electrical connections on the tiles had become over the course of the year.

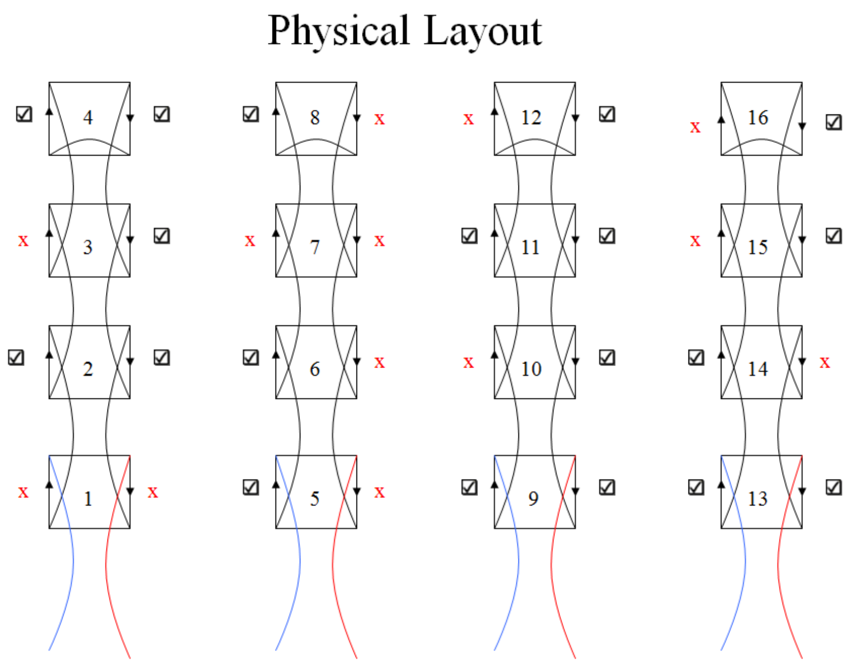

Figure 2.3 Layout of the roof tile prototype, showing connections broken before deconstruction

2.1.3 Mechanical failure

Given that each string was wired in series, a single mechanical failure in any one of the connections caused a break in the electrical contact, meaning that no current would be able to travel through the system and no useful power generated.

The main source for mechanical failure was at the connection between the ends of the solar panel slices and the wires used to connect one roof tile to the next. These were constructed such that a thin, flexible metal strip connected the solar panel and the fairly large-gauge wire by being soldered at either end. This thin strip of metal tended to corrode when subjected to outdoor conditions, which made it even more brittle and fragile than it was to begin with. Several of these strips had corroded to the point of breaking while in the field, and in the course of dismantling the installation and conducting tests on the individual tiles, few connector wires remained, despite the care with which the samples were handled.

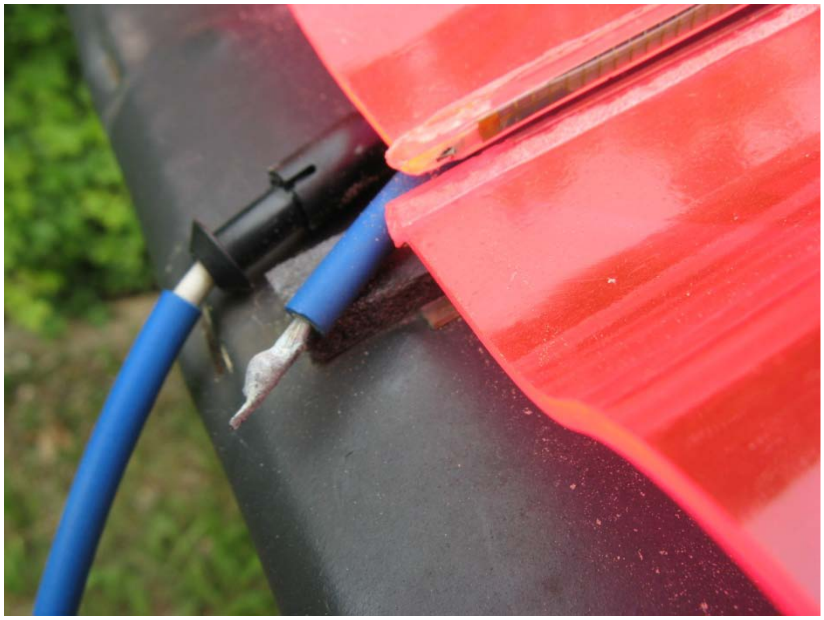

Figure 2.4 Corrosion and damage to the electrical leads and coating on the solar cell

Were these tiles to go into production in a large scale for use on homes, special care should be taken when redesigning the connection between the panels and the wires used to connect them in order to ensure a minimum level of resilience. Roof tiles should not need to be treated with kid-gloves, and making this particular connection more robust would improve their durability during installation as well as over their lifetime in use.

Another source for mechanical failure of the tiles was in the manner in which the solar cells were affixed to the fluorescent tile. In the arrangement used, 4 tiles were soldered together at the ends to maintain electrical contact, and were then both attached to the edges of the tile with an epoxy and coated in the same epoxy to protect the tiles from damage. The epoxy was chosen because of its good optical clarity and refraction index, which reduced the losses that would be present if an air gap were present between the emitted light and the solar panel. After disassembling the installation and inspecting the individual tiles for damage, the thick epoxy coating did provide for significant protection from the elements, when applied correctly. This particular prototype was constructed by hand, which left many opportunities for deviance from the ideal assembly conditions and so allowed for a wider view of the various ways in which the design could age. In several instances, the epoxy layer was very thin, had bubbles, or formed an incomplete seal around the solar cells by having been applied unevenly around the edges of the solar panels. In these cases, water was able to seep in through the cracks or holes in the seal and corrode the metals present. This occurred both in the overlay on the solar cells themselves and the solder connecting them.

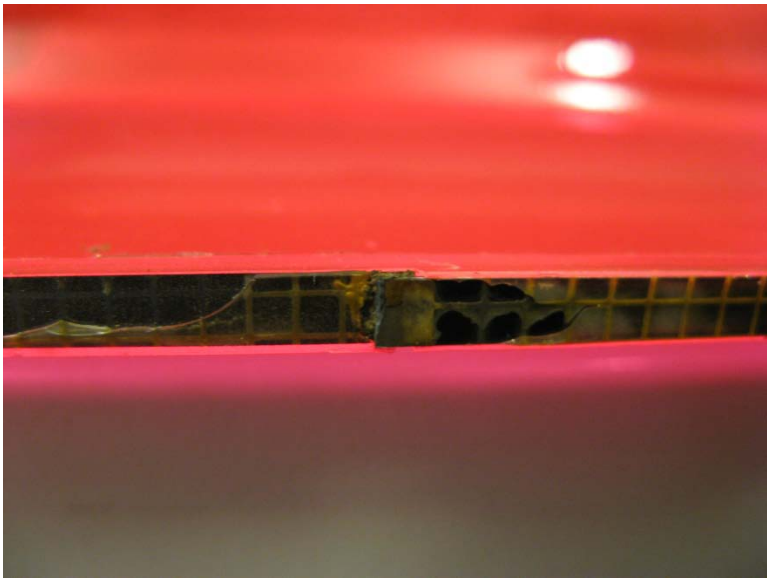

Figure 2.5 Corrosion at the soldered connection between solar cells

In these cases, the volume expansion caused the brittle epoxy to crack and fracture, allowing for even more corrosion to occur. This caused the protective epoxy coating to flake off, peel away, and in some cases break off in significant quantities, occasionally causing a piece of the solar cell to break off with it.

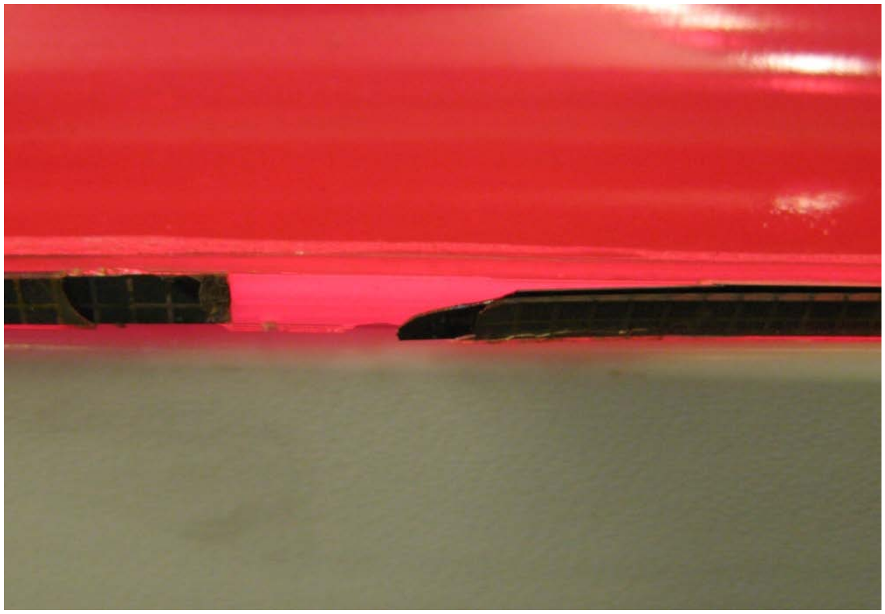

Figure 2.6 Brittle damage to the epoxy allowing for damage to the solar cell

This suggests that a more thorough method should be explored for applying the protective coating, and perhaps a more flexible epoxy that would be less prone to brittle fracture could be used to protect the photovoltaic cells from water-related damage. Another measure that might be taken to protect against the loss of electrical contact between the cells would be to use a solder that would be less prone to corrosion in the presence of water, in the case of a failure or misapplication of the protective epoxy coating.

2.2 ELECTRICAL TESTING

2.2.1 Electrical test premise and setup

Given the condition of the tiles during disassembly, it was clear that there was not any overall power generation coming from the prototype. In order to see how extensive the damage really was, both sides of each tile were tested for power generation between the end leads, or remaining conductive metal tape if no lead remained.

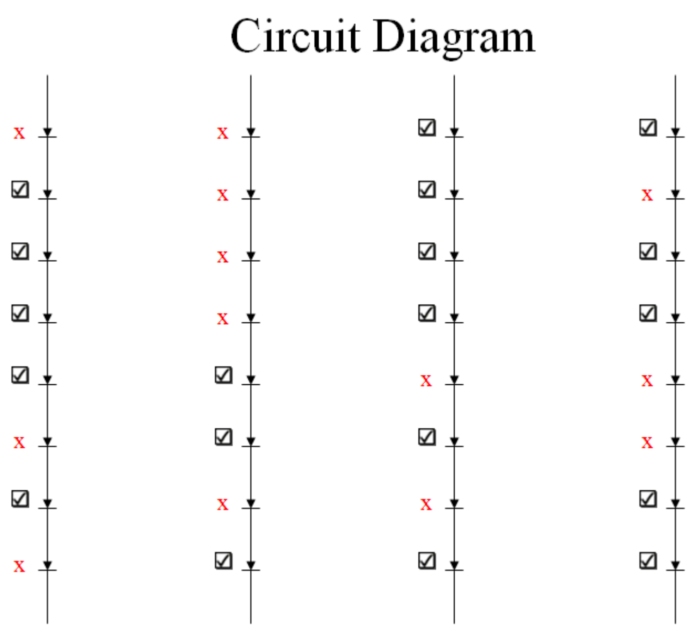

Figure 2.7 Circuit diagram at time of deconstruction, showing faults present in each series of diodes

First, a voltmeter (in our case a multimeter) was used to discern if there was any viable voltage being generated in the solar cells at all. In the samples that were able to generate a voltage, they were tested fully under the small-scale solar simulator at nominal STC for open-circuit voltage and closed-circuit current.

2.2.2 Electrical test results

Marks in Table 3.1 denote that no electrical voltage could be measured at the lead or remnant thereof, and that the leads on that edge of the tile were broken off in use or deconstruction of the prototype. The electrical leads in particular were subject to damage over time: many broke off in a form of mechanical failure of the system. Some of the ones that lacked leads were still capable of generating a voltage, however some of the tiles that still had electrical leads had sustained other damage along the connections such that they could not.

Table 2.1 Damage after construction

		Side A			Side B	
tile	lead 1	lead 2	leads intact	lead 1	lead 2	leads intact
1			x	x	x	x
2			x	x	x	x
3						x
4			x			
5	x		x	x	x	
6	x	x	x	x		x
7	x	x		x	x	x
8	x		x			
9						x
10	x	x		x	x	
11			x	x		
12	x		x	x	x	x
13				x		
14	x	x	x	x		x
15	x		x	x	x	x
16	x		x			x

Table 2.2 Voltage and current of functioning tile sides

tile	side	Voc (V)	Isc (A)
1	A	1.57	0.012
4	A	1.386	0.018
4	B	1.601	0.018
8	B	1.597	0.014
9	B	1.19	0.008
11	A	1.585	0.022
13	A	1.292	0.012

Voc range 10 V, Isc range 15 A

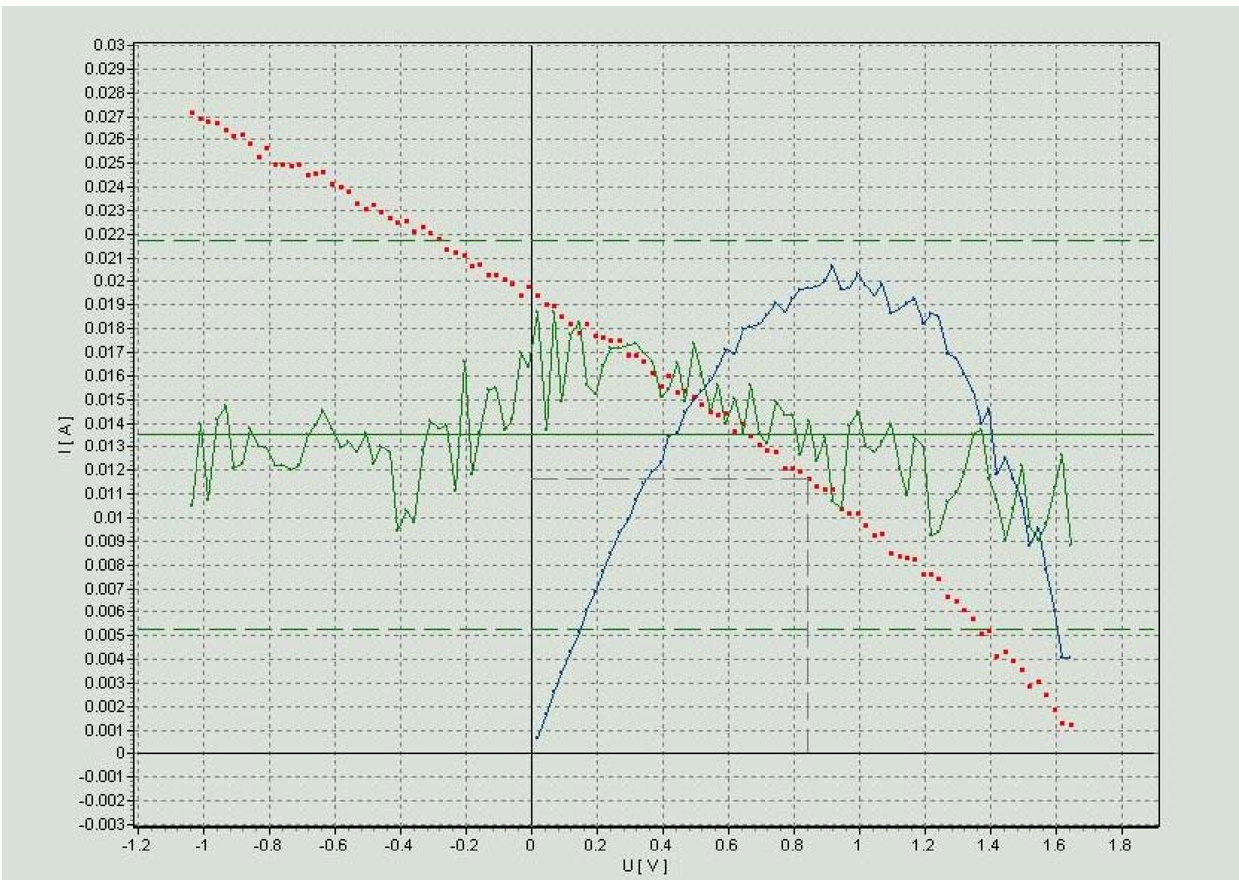

Figure 2.8 Example I-V Curve, Tile 11

It was mentioned earlier that for the four strings which constituted the 16-tile assembly, everything, from the solar cells to the tiles themselves, was connected in series. This meant in practice that when a single connection failed-- from the solder between two slices of solar cell being to corroded to conduct the current to the connecting wires breaking off - that the electrical connection between the entire string of four tiles was compromised. The greater voltage between the ends of the string allows for better power generation, but as owners of Christmas lights in years past have found, connecting elements in series makes it difficult to identify the faulty element. Were these tiles to be installed on an actual roof, with all the difficulty of access it presents, performing maintenance on the tiles would be even harder. I would recommend shorter strings in series, which could be later connected to each other in series to preserve the voltage necessary for power generation, but with indicators before the connections in order to better pinpoint sites of failure. An ability to remotely test individual tiles for a voltage generation over the solar cells in the presence of sunlight would also reduce the amount of time spent on the roof performing maintenance, and allow for longer strings. Minimizing the time needed to diagnose and address the problem would allow for a higher voltage, for a maximum power generation with a minimum risk that a single faulty connection would cause extended failure of the system.

2.3 LUMINESCENT PROPERTIES

2.3.1 Degradation of the luminescent element

Aside from the corrosion in the electrical elements, the other component that was likely to experience time-dependant degradation was the fluorescent dye in the collector. Roof tiles are expected to be viable for extended periods of dime due to the expense and difficulty associated with maintenance and installation. The companies producing roof-mounted flat-panel solar cells have more experience with ageing effects, having dealt with the technology longer. They also tend to feature non-integrated installation, so the solar panels can be removed and replaced without affecting the integrity of the roof, where the roof-tile model would require more effort.

These fluorescent collector tiles experienced problems in the buildup of dust and pollen familiar to traditional solar panel installations. Much like with flat-panel solar panels, especially in areas rich in airborne particles such as fields with pollen or urban areas with airborne pollution, matter in the air tends to settle on the surface of the tiles and obscure the incident irradiation. This problem is usually dealt with through the application of specialized coatings on the panels, which discourages a significant buildup and allows for what pollen or pollution might be coating the surface to be washed away with the next rain. These tiles would also benefit from such a coating, as the samples in the installation had built up a significant layer of dirt and pollen which interfered with the incident irradiation reaching the fluorescent collector.

2.3.2 Fluorescent test configuration

The tiles were covered in dust and dirt after a year outside, which obviously impaired the concentrators' ability to redirect sunlight. They were cleaned with soap and water, and mounted on a special test bench fabricated for the purpose of holding the tiles with as little contact as possible. This was to reduce the instances in which the total internal reflection of the tile was broken, and allow the maximum amount of light to travel through the matrix and reach the detector at one of the edges.

We used a small-scale solar simulator at STC to measure the luminescent transmission of the tiles, and compared the results to tiles that had been indoors and shielded from light for the duration of the lifetime of the installation, so they would have no damage from UV radiation.

The simulator was set to nominal STC, but did have a certain amount of inhomogeneity in the light emitted.

Figure 2.9 Small-scale solar simulator

The 42x42 cm square area of the simulator was divided up into 6x6 cm sections and each measured for incident irradiation, keeping in mind that ideally it should read 1000 watts per meter squared over the entire area.

Table 2.3 Values of irradiation (W/m^2) at corresponding areas of the solar simulator

915.4	889.4	866.4	900.6	869.6	897.5	922.4
886.4	890.5	881.8	965.7	918.9	912.7	923.3
896.4	951	880.2	895.6	913.6	930.6	917.7
890.8	936.1	872.8	901.1	901.3	915.5	913
894.6	904.9	895.3	927.1	902.2	911.8	905.7
882	892.9	874.8	917.1	888.8	884.6	868.3
784.4	662.9	637.8	672.6	658.2	630.6	682.7

Y ↑

X →

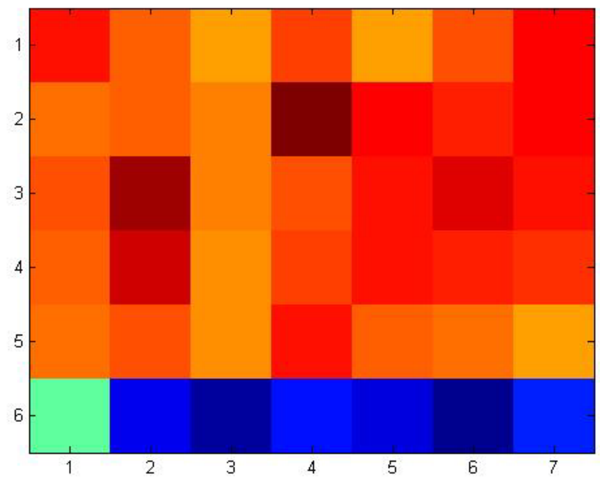

Figure omogeneity in the solar simulator: Darker red corresponds to higher irradiation

2.3.3 Fluorescent test results

After cleaning, each of the 16 roof tiles' edge emittance was measured with an Ocean Optics HR4000 spectrometer. This was compared to the emittance of seven similarly constructed tiles which had remained in a lightless closet for the life of the prototype.

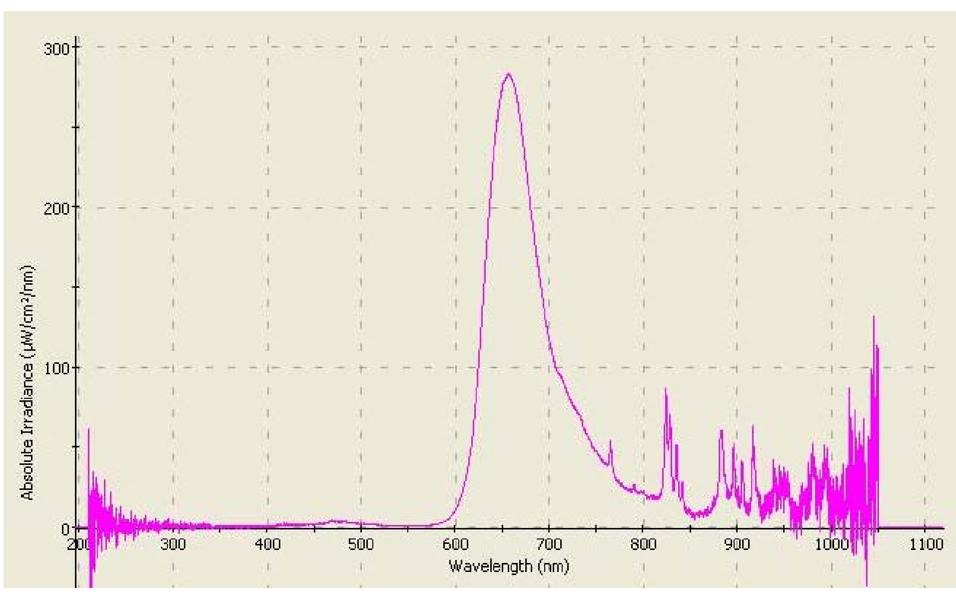

Figure 2.11 Example of spectral analysis of tile emission, tile 11

Table 2.4 Emittance of tiles, both indoor and outdoor

outdoor tile	W/m^2
1	282
2	287
3	278
4	252
5	295
6	262
7	239
8	249
9	240
10	308.5
11	297.3
12	262
13	227
14	275
15	235
16	286.7

stdev	24.97688
average	267.2188
uncertainty @ 95% C	0.183201
% uncertainty	0.068558

indoor control tile	W/m^2
1	357
2	361
3	485
4	391
5	381
6	379
7	389

stdev	43.07911
average	391.8571
uncertainty @ 95% C	0.215474
% uncertainty	0.054988

% difference	37.82217
t calculated	-7.14726
degrees of freedom	6.500032
rounded deg of freedom	6
T in table	-1.943

cannot conclude that outside transmission < inside transmission

The measurements were integrated over 20 ms and averaged over 1000 measurements per sample, and while the two populations did show a 37.8 percent difference in the averages of the emittance, a Student's T test showed that it could not be said with 95% confidence that the set of samples which were outside for a year had statistically significant lower readings for emittance than those shielded from light. This suggests that perhaps a small amount of fading occurred, but in the course of a year of use in Munich, the fading was by no means catastrophic. The formula for the dye could probably be used in a large-scale production of the product without much ill effect, but a longer term study or increased sample size would be of use to see if the performance of the dye degraded.

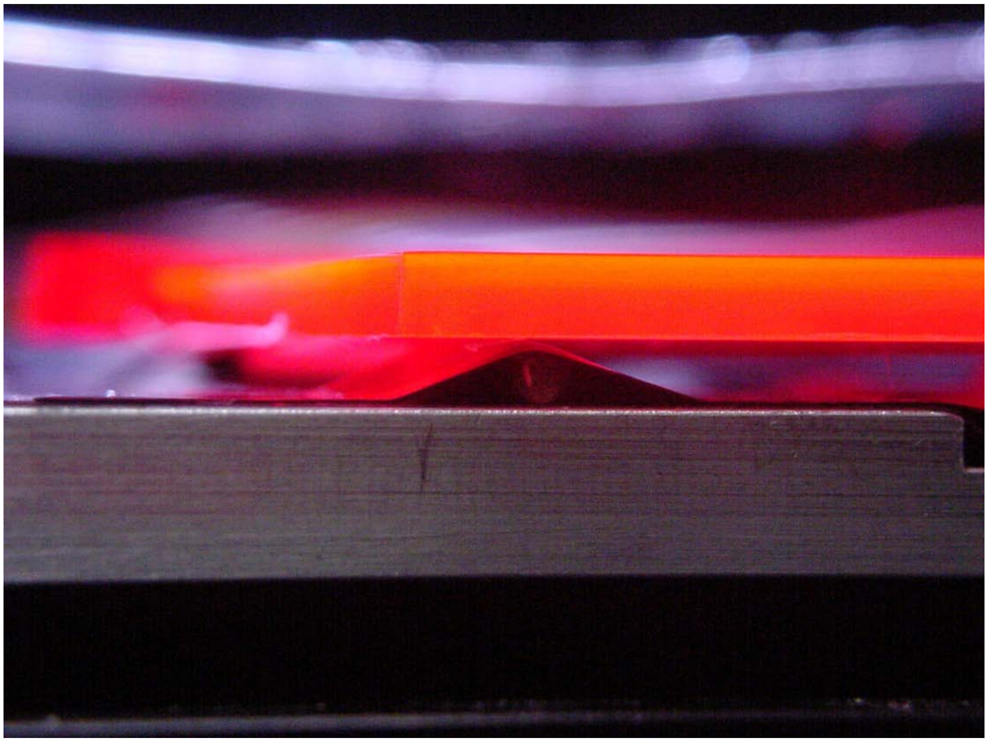

Figure 2.12 Edge of tile illustrating light transport under normal laboratory light

3.0 PERFORMANCE COMPARISON

3.1 TECHNOLOGIES COMPARED

Some work has also been done on determining the efficiency of the large-scale Polar Bear prototype over its lifetime on the test bench, particularly as compared to a more standard monocrystalline module. In particular, we aim to determine if the Polar Bear is proportionally better on cloudy days, which would give it a definite market niche given its reduced price per watt of electricity generation. Some work on this has been done in the past and has shown promising results in tracking and stationary performance for other configurations of fluorescent concentrators (Pravettoni, Virtuani, Zaaiman, Galleano, Kenny, Dunlop, Bose, Barnham 4). We aim to show that even under stationary angled installation conditions, our fluorescent concentrator can operate at an advantage over traditional flat-panel cells.

3.1.1 Conventional flat-panel photovoltaic cell

In order to gain some insight into the comparative performance of our particular fluorescent concentrator technology to the market standard, a monocrystalline silicon flat-panel solar module, we installed examples of both technologies in the outdoor test bench in order to gather data. The monocrystalline flat panel used in our tests was a Sanyo HIT model (HIT Power 205), with an area of 1.16 meters squared and a maximum peak rated power of 205 Watts.

3.1.2 Fluorescent concentrator analog

In order to test our particular fluorescent concentrator technology, we needed to create a prototype which replicated the flat-panel module used as a control in as many aspects as possible, to reduce variation from other sources. For our test module, this meant that a fluorescent collector of comparable dimensions to the standard silicon module. Because of the issues with structural integrity at such a size, the fluorescent-dye impregnated plastic must be molded in a way as to fulfill certain flexural stiffness requirements. The module used in our tests had four sets of square pyramids separated by flat ribs. This configuration, molded from a uniform thickness layer of plastic, increased the surface area marginally, but primarily served to increase the stiffness to a point that it could be mounted to the test bench alongside the silicon module without bending and snapping in the wind.

3.2 TEST CONDITIONS

The above configuration and the fluorescent collector were both mounted on the same stationary test bench at an angle of 60 degrees to the horizontal, and experienced identical irradiation, ambient temperature, and minimal shading over the duration of the experiment. Over the course of three months, the two solar cells experienced the same wear and ageing in the outdoor conditions of Munich. Munich as a location to study solar technology has several advantages-- it has a relatively large amount of sunshine compared to the rest of Germany, and a relatively accommodating government compared to the rest of the world in terms of funding. Comparative data was collected over the course of three months, but also compared over the course of an average sunny day in order to show the behavior in the presence of primarily direct irradiation, and an average cloudy day to show the performance when experiencing mainly diffuse irradiation over the course of the day.

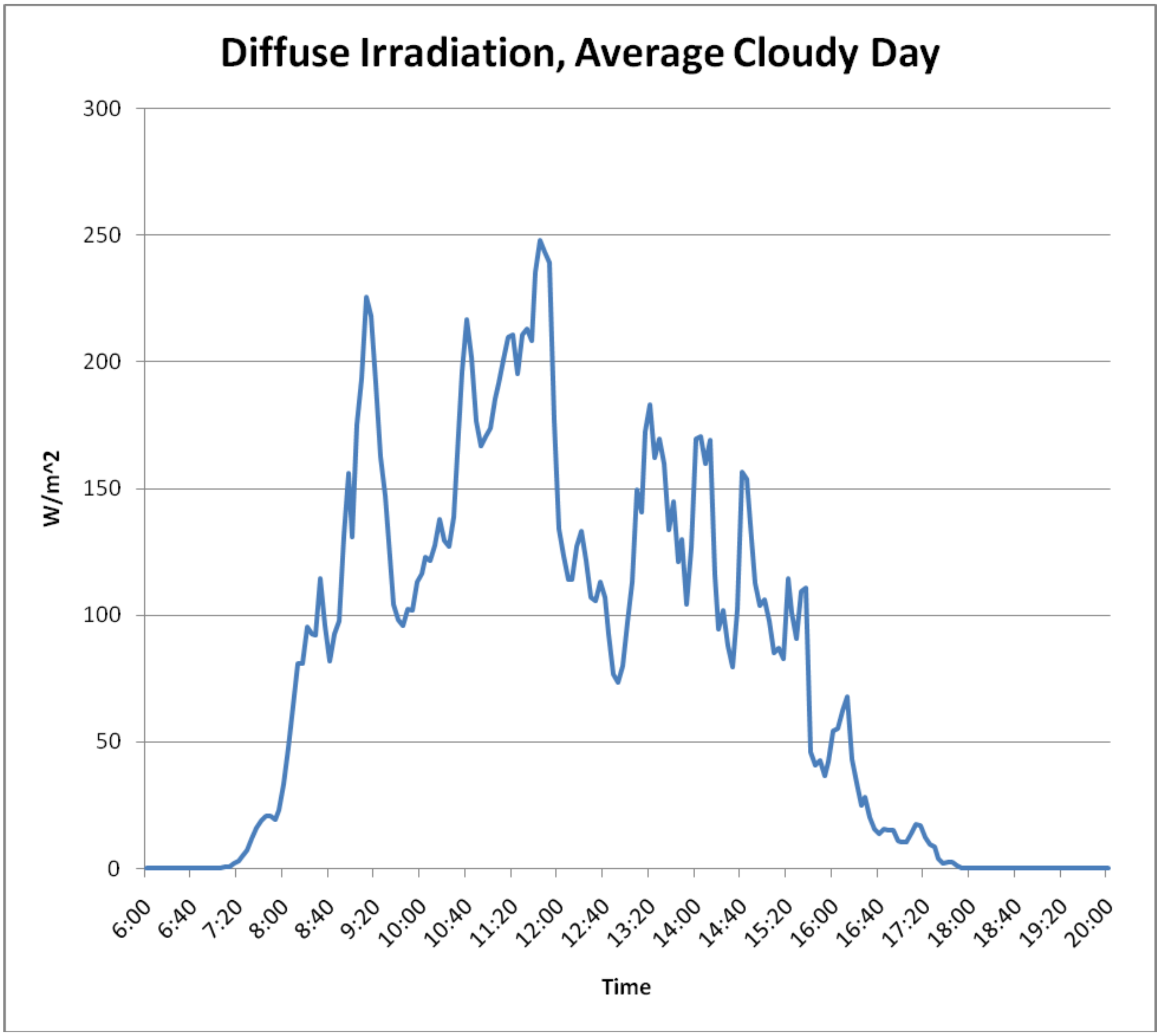

Figure 3.1 Irradiation on a cloudy day: mainly diffuse

As can be seen in figure 3.1 and figure 3.2, diffuse irradiation (as collected by a weather station next to the modules) tends to be lower and more constant over the course of the day. On a cloudy day, the diffuse irradiation makes up the balance of the incident irradiation on the modules. On the sunny day, both the total irradiation and the diffuse irradiation were tabulated, in order to illustrate the difference between diffuse and direct irradiation over the course of a day.

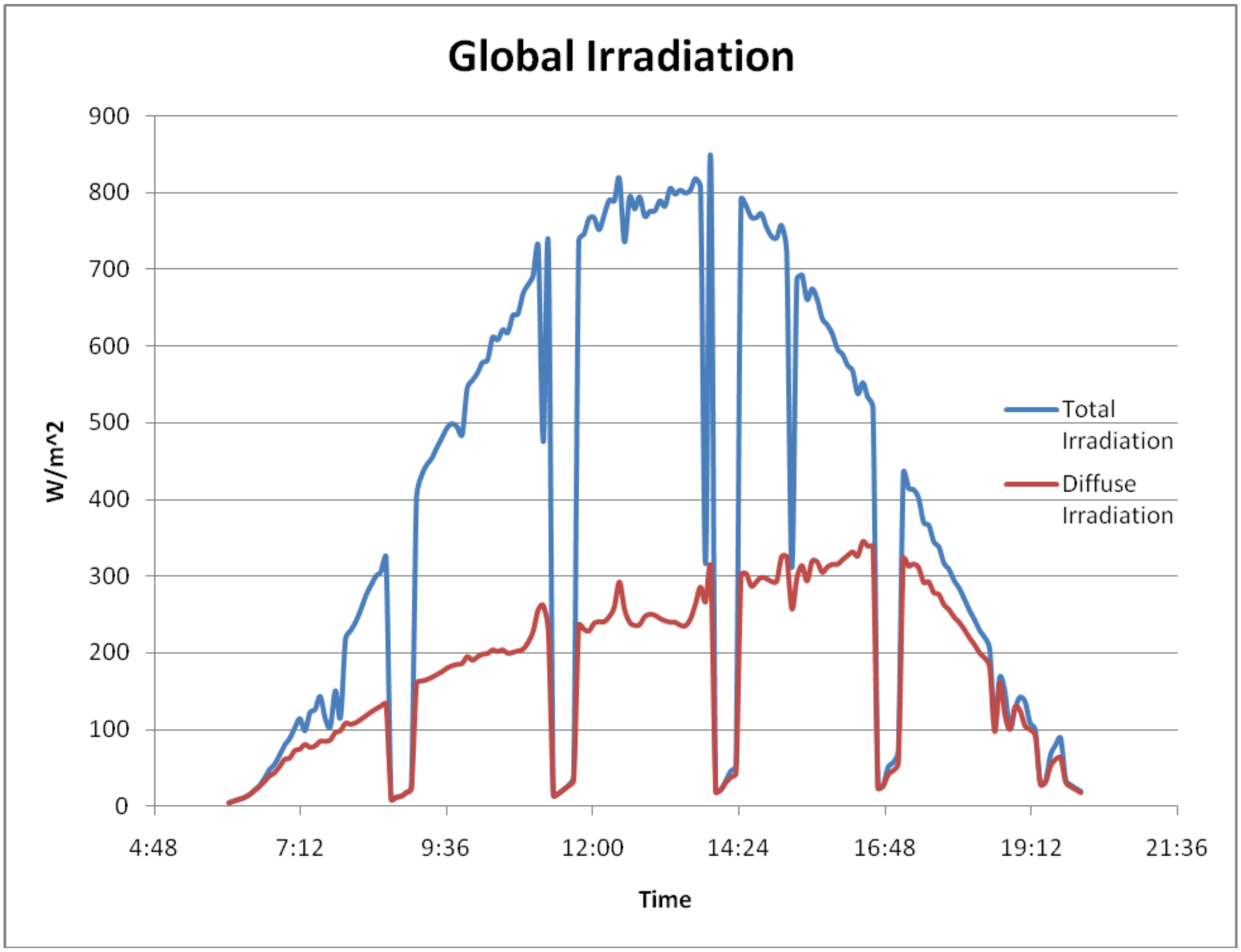

Figure 3.2 Total irradiation over the course of an average sunny day

When discussing STC, or Standard Test Conditions, the irradiation used is a constant 1000 Watts per meter squared, at an air mass of 1.5, and a temperature of 25 degrees Celsius. This is meant to standardize the conditions under which modules are measured, and test them at conditions close to what could be expected in the field. An irradiation of 1000 Watts per meter squared is not unheard of at peak irradiation on a sunny, clear day. Our location in Munich will occasionally reach this level of incident irradiation, but on this particular day it only reached between 800 and 900 Watts per meter squared.

3.3 ANALYSIS AND RESULTS

When dealing with solar modules it makes sense to look at the total output, though particularly in the case of concentrating systems efficiencies should be considered as well. By looking at the power generated per Watt peak of rated power for the module, it can be shown how effectively a module is performing compared to the rated optimal performance for that particular model. One of the premises of a concentrator system is that it uses the solar cells in a more effective way by concentrating more light on the active component than would otherwise occur, so our prototype aims to outperform the standard module in this measure in particular.

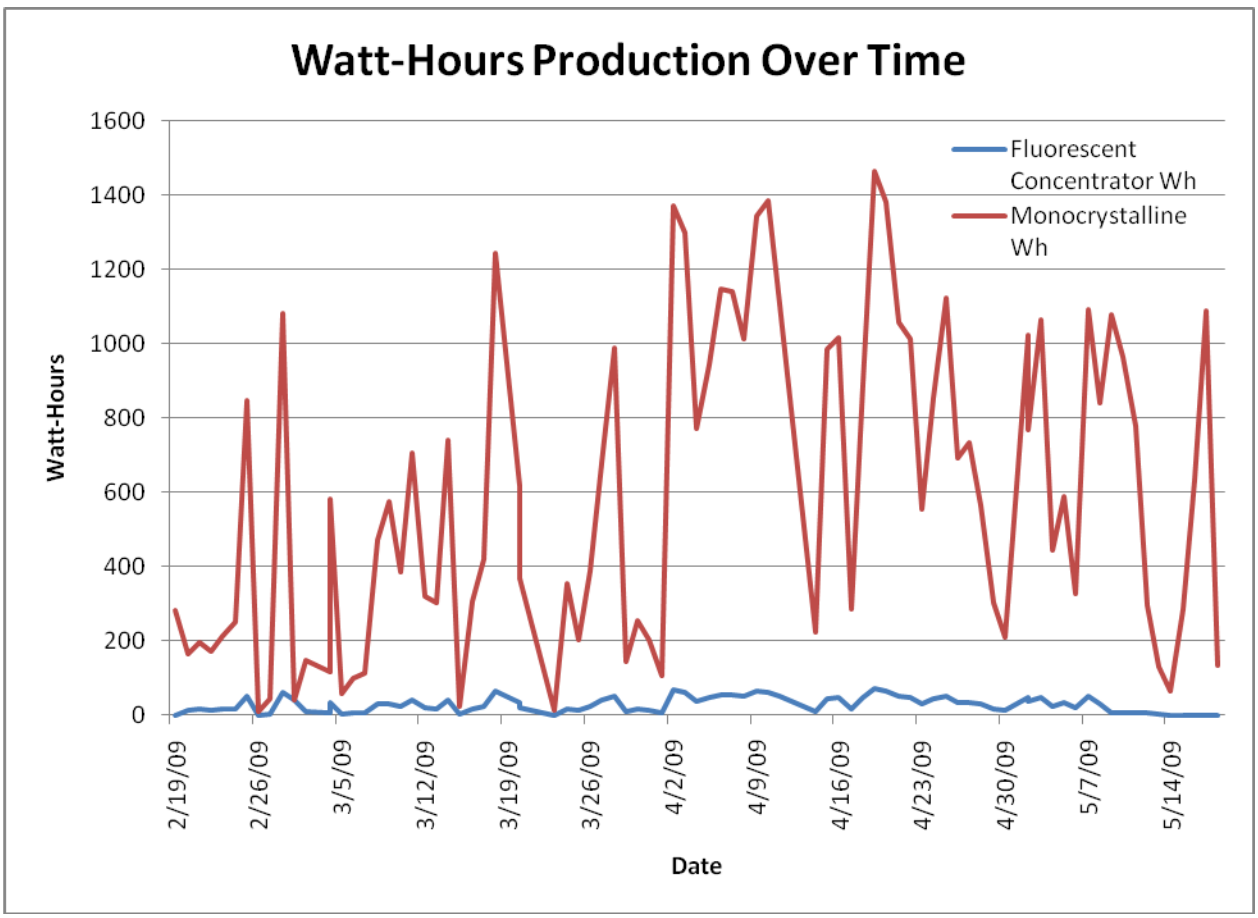

Figure 3.3 Total power generated over a 3-month test period

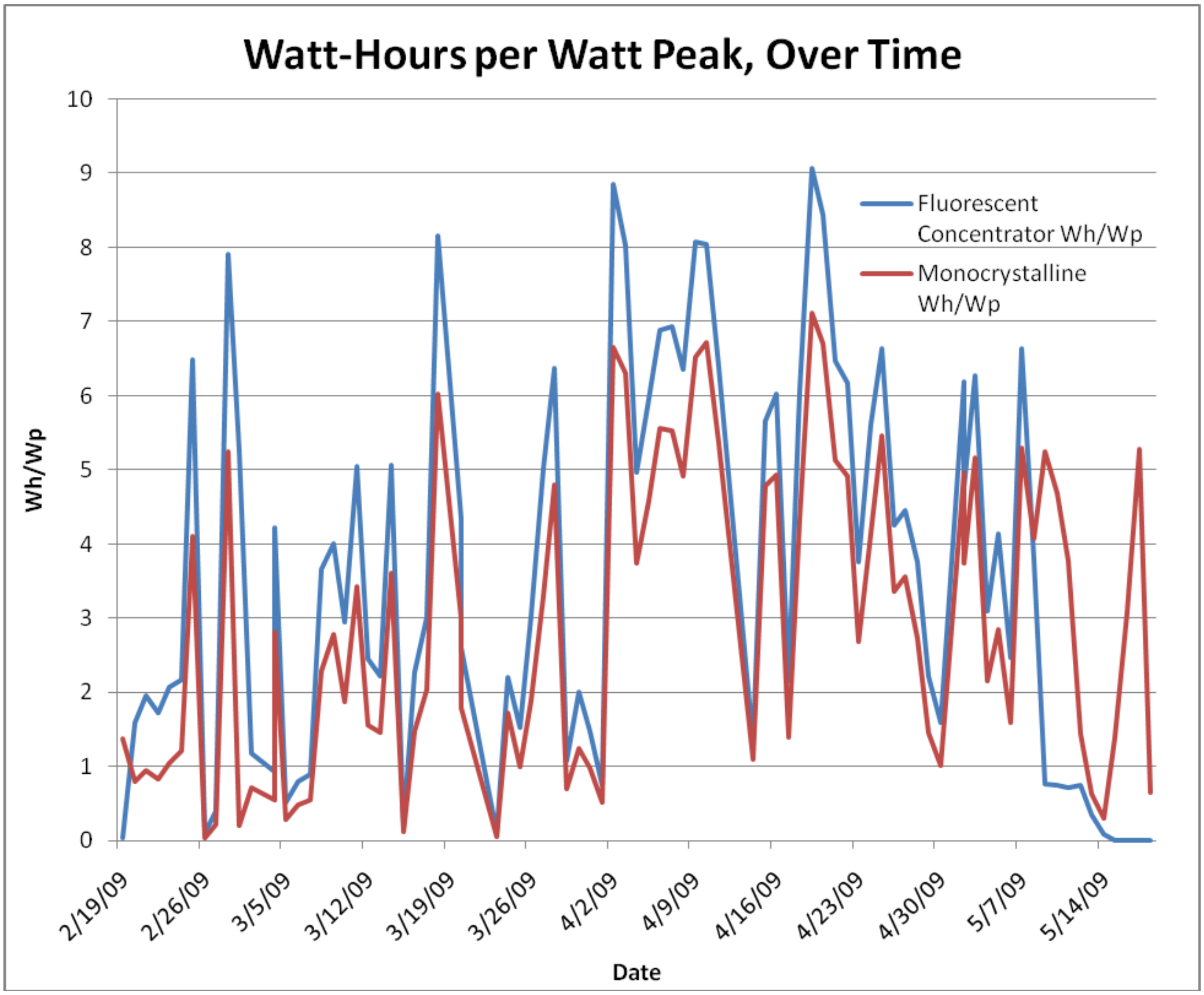

Figure 3.4 Power produced per Watt peak rated performance over the course of three months

We looked at performance over the span of three months, from the middle of February to the middle of May in 2009. This allowed us to see the performance of both modules in a range of different situations-- from cloudy, cold winter days to sunny warm days at the beginning of summer. Figure 3.4 shows that, even given varying conditions the cells in the Polar Bear prototype outperformed the control module in terms of Watts produced per Watts rated peak.

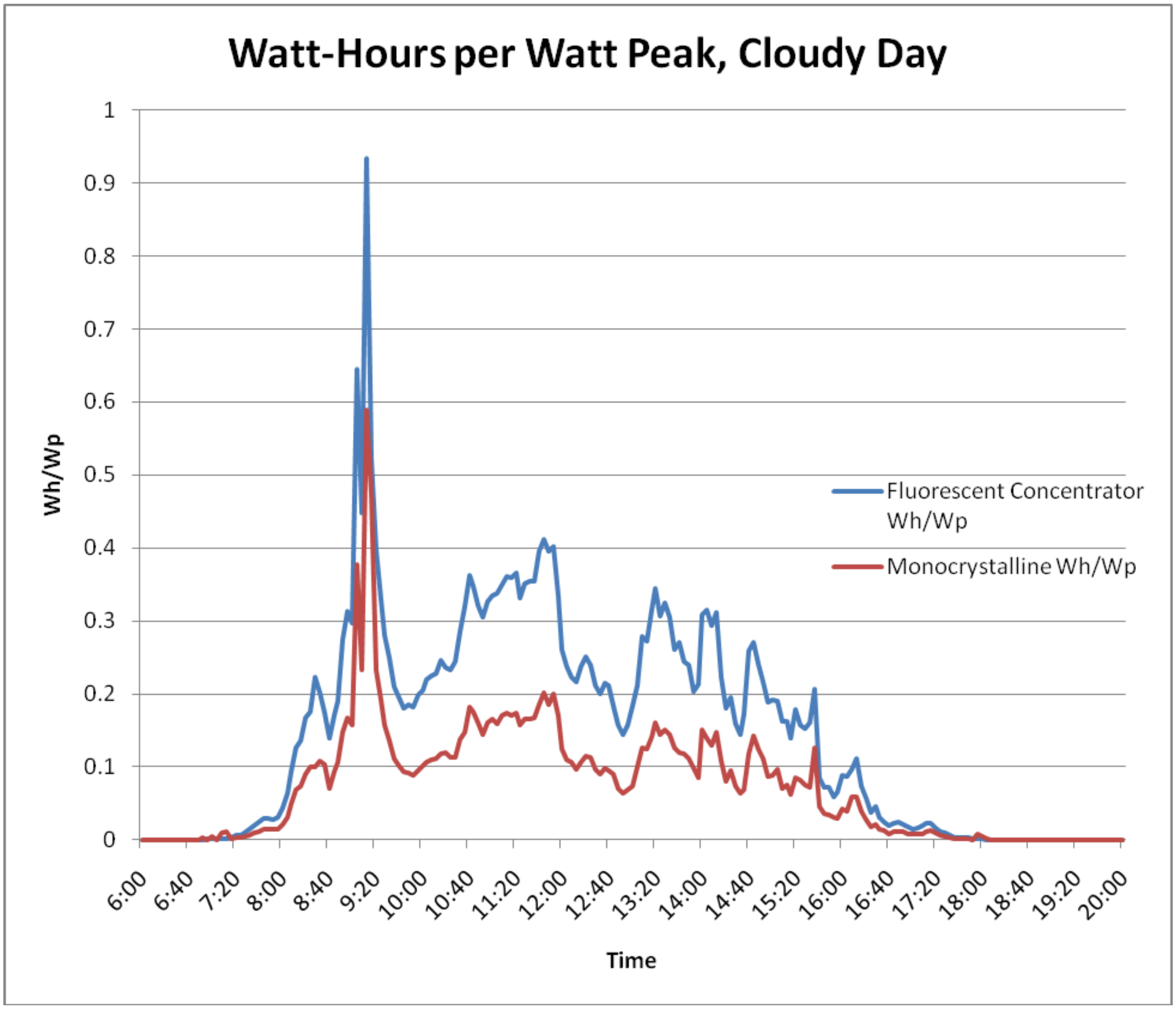

Figure 3.5 Comparative performance on a cloudy day

While looking at performance over time is a useful metric by which to measure the modules, interesting trends emerge when narrowing the focus of our analysis. When compared in the presence of mainly diffuse irradiation, on an average cloudy day, the Polar Bear prototype clearly outperforms the control module. This has major implications for its viability as a consumer product. Traditionally, collecting diffuse irradiation has been of lesser importance to manufacturers of photovoltaics, but much of the consumer base for a product such as ours lives in climates where direct irradiation may not be present year-round.

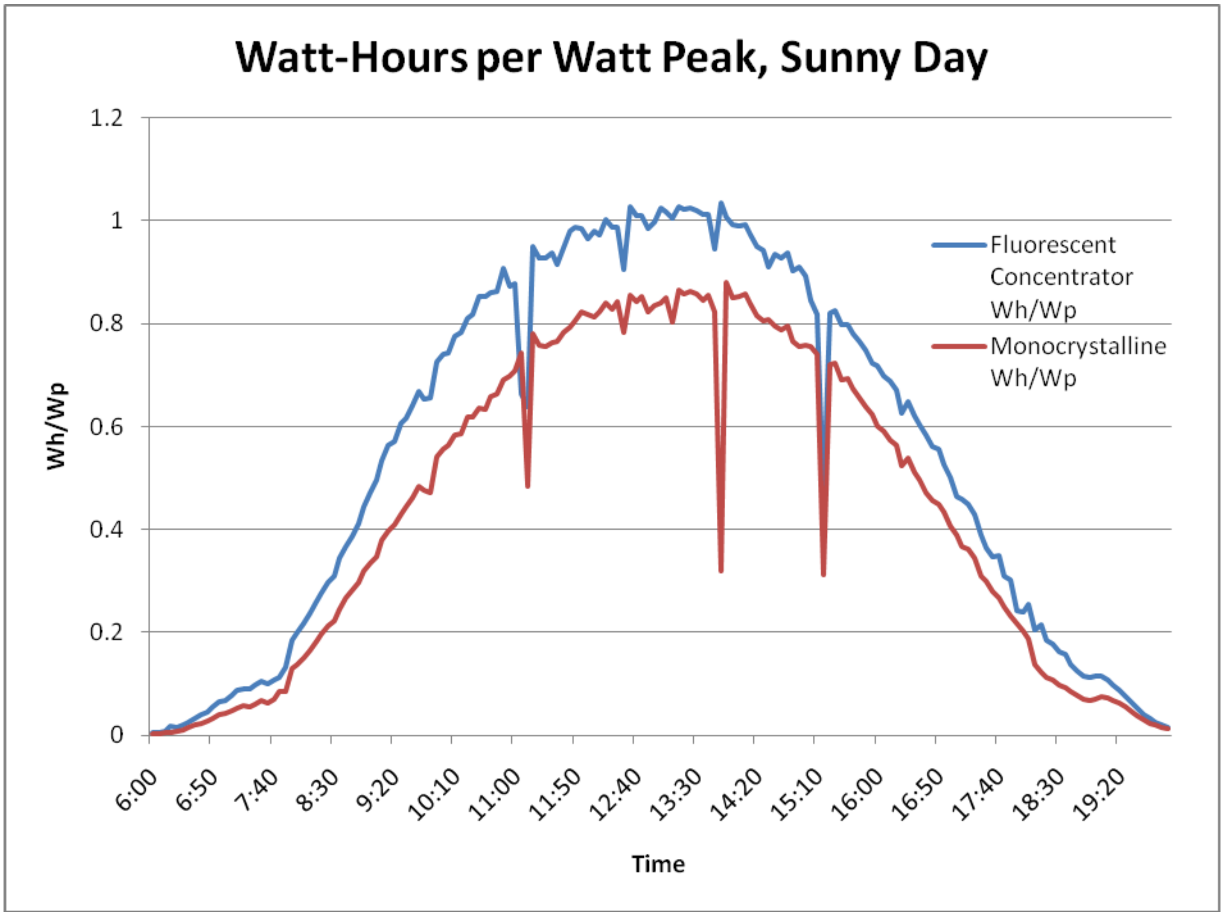

Figure 3.6 Comparative performance on a sunny day

Even when compared on a sunny day, when direct irradiation has a much greater presence, the Polar Bear module performs on par with or better than the control module. This shows that, given a certain area of silicon photovoltaic material, usually the expensive component in a solar power system, the consumer would not be at a disadvantage using it in conjunction with our fluorescent concentrating system on even sunny days.

4.0 CONCLUSIONS AND FUTURE RESEARCH

4.1 CONCLUSIONS

The emerging field of luminescent concentrators and photovoltaics seems a logical direction for GE. With the research facilities capable of further developing a new and promising technology and the market presence already secured, GE could bring fluorescent concentrators to the forefront of the consumer market for green technology.

On the whole, the roof-tile system seems a logical direction to go with the fluorescent concentrator technology though there is still a good amount of work to be done. Our research on the current prototype shows that the matrix used seems to be a good fit for the product, though more extensive testing should be done on the dye over longer periods of time before being put into mass production. The electrical connections and optical interface should also be redesigned to be more durable and weatherproof, and also undergo more extensive testing over longer periods of time.

The analysis of the performance of the fluorescent concentrator was able to show that even when compared to a more standard monocrystalline module, our concentrator prototype was able to perform consistently at equal to or better rates of efficiency. This more than anything shows that the technology could be brought to market, with minimal risk to the company and the consumer. At a lower cost to produce and install, it could offer an entry into green energy for consumers who would otherwise not take on the initial investment of photovoltaics.

4.2 FUTURE TRAJECTORY OF THE PROJECT

There is much work still to be done on the development of the fluorescent concentrator-particularly in roof-tile form before it is introduced to the consumer market. The original plans for the Polar Bear project involved a solar thermal element in the roof tile, which has yet to be developed into a combined prototype. Even in the purely photovoltaic model, studied here, improvements can be made and further studies undertaken before the product will be ready for mass production. In the end, however, I fully expect fluorescent concentrator photovoltaics to become a staple in energy production in an increasingly environmentally-conscious and green world, and GE is in a good place to develop and hold a strong place in the market.

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