Alternative Renewable Energy Resources

An Interactive Qualifying Project Report

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by

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Professor Mayer Humi, Advisor

1. Nonrenewable Energy Resources
2. Alternative Energy Resources.
3. Solar Energy

Abstract

With the waning supply of fossil fuels, the need to explore alternative renewable energy sources is vital to satisfy energy demands. This project analyzed the current reserves and consumption of coal, natural gas, and oil to predict how long they will last. Alternative energy was then considered, including an in-depth analysis of a photovoltaic energy system to satisfy the energy needs of WPI. The system was determined to be economically feasible, provided that sufficient federal grants were obtained.

Authorship Page

All group members, Andrew Law, Sara Fowler, and Jeffrey Wolf-Jaworski contributed equally to this project.

Table of Contents:

Table of Figures:

Table of Tables:

1. Executive Summary

The objective of this report was to examine nonrenewable and renewable energy resources and determine the most effective methods by which an impending fossil fuel crisis can be averted. The remaining reserves and consumption trends of natural resources were of utmost importance in predicting the timetable that exists before fossil fuel-dependent economies, such as the United States, will be forced to search for replacement energy sources. The implementation of renewable energy systems before this occurs will help the United States make a smooth transition from fossil fuels to renewable energy, and drastically aid in the movement towards stabilizing and improving the environment, which has suffered immensely from fossil fuel consumption.

Obtained from the U.S. Geological Survey and other resource-oriented organizations, the most recent estimations concerning oil, natural gas, and coal reserves were evaluated with respect to recent trends in production/consumption rates. Using linear regression analysis of the production/consumption data, it was determined what future rates will be, and how long the current reserves would last based on these rates. For oil, it was determined that reserves would be exhausted between 2038 and 2052. For natural gas, it was concluded that reserves would be exhausted between 2047 and 2049. For coal, it was determined that reserves would be exhausted between 2115 and 2121.

The analysis of renewable energy resources included hydropower, wind energy, and biomass conversion, but the primary focus was based on solar energy systems. In terms of a global solution to the impending fuel predicament, the possibility of launching geostationary solar power satellites was considered. Though in theory these satellites could provide more than enough power to supply the entire earth's needs, the cost of implementation would be astronomical. The size of these structures would require an installation process resembling the construction of the international space station, but at a larger level. Another limitation to this type of renewable energy source lies in the transmission of energy from the satellite to earth. Microwave transmission of energy would circumvent problems associated with cloud cover, but the possible associated environmental and health risks are not known. Also, due to the distance of transmission, the microwave receptor site would have to be enormous.

In terms of a more isolated implementation of solar energy, a system was designed and analyzed for WPI. The solar radiation exposure of Worcester was obtain and applied to various panel systems and orientations to determine the amount of energy produced. Depending on the system, 5.4% to 11.6% of WPI's annual electricity consumption could be generated. The environmental savings of these systems, in terms of prevented carbon dioxide emissions, were between 411 and 3723 tons per year. To ascertain the economic feasibility of these systems, a net present value analysis was completed. Based on the initial costs for implementation and guaranteed incentives, there would be still a net loss of millions of dollars after 25 years, the lifetime of a system warranty. However, there are a number of supplemental incentives and cost cutting measures which, if fully exploited, would make a solar energy system at WPI indubitably feasible.

2. Introduction

Of the many political and social issues that are prevalent in the world today, perhaps the most pressing issue concerns the invaluable and ever-decreasing natural resources that fuel modern society. The current U.S. involvement in Iraq has caused many skeptics to question whether the U.S. is in the region to spread democracy or to maintain a firm hold on oil, the lifeblood of its world-leading economy. Regardless of the motives of those in authority, it is undeniable that developed nations are over-dependent on fossil fuels. During the oil crisis of the 1970s, the U.S. government began funding research and development programs for renewable energy resources. However, when oil prices dropped back down to reasonable levels, these programs were aborted, and advancements were significantly slowed. If these programs had continued with due diligence until today, perhaps renewable energy systems today would be more efficient and financially feasible than conventional nonrenewable energy systems.

Instead of focusing on what might have been, it is necessary to look forward and be proactive concerning the solution to this impending oil crisis. This is not an issue that cannot simply be set aside and left to future generations because the affected generation is our own. Within the next fifty years, it is expected that fossil fuel resources will be either completely consumed or severely limited and renewable energy technologies will be standardized. The social and environmental impacts of the conversion to renewable energy resources are astounding.

As students studying civil, biomedical, and electrical engineering, the study of alternative renewable energy resources is of significant interest to each of us. In an electrical engineering sense, this report deals with the development and implementation of more efficient energy generation from renewable sources and the transmission of high-energy microwaves from geostationary satellites to earth. In a civil and biomedical engineering sense, the environmental and health risks imposed by current consumption of fossil fuels is a global issue that is cause for concern.

In the following report, predictions are made concerning the longevity of remaining fossil fuel reserves. The feasibility of renewable energy resources are then examined, with most of the focus placed on solar energy systems. Solar energy implementation is considered at the residential, industrial, and global level. The industrial-size system deals with supplying WPI’s energy needs via solar panels. The global level discussion focuses on solar power satellites.

3. Literature Reviews

3.1 Out of Gas by David Goodstein [1]

A frequent topic of conversation these days is the recent trend of increasing gas and oil prices. Though most would tend to disagree, the continuation of this trend at a more rapid rate could possibly be the most blessed event in recent history. Not only could it mean changing the mindset of the masses towards more fuel-efficient ways of life, it could prevent a natural disaster that would not only disintegrate our current standard of living, but perhaps result in complete and utter destruction of life on the Earth. This predicted natural disaster is the exhaustion of remaining fossil fuels and/or the decay of life-sustaining environmental conditions due to fossil fuel expenditure.

Though it is not the most detailed and all-inclusive book on the subject, David Goodstein's Out of Gas provides an interesting and informative narrative of the past, present, and future states of fossil fuels, energy, and Earth's atmosphere. Its rather ironic that despite incredulous technological advancements and elevated standards of living, the future and well-being of the Earth is growing dimmer with each passing day. The most poignant statement in Goodstein's book is not found within the actual chapters, but rather in the simple forward: "To our children and grandchildren, who will not inherit the riches we inherited".[2]

The first oil well was dug in 1859 in Pennsylvania, contributing in large part to the ensuing Industrial Revolution. Since that time, roughly 50,000 oil fields have been discovered. However, over 50% of oil has come from the 40 largest oil fields. In the 1950s, a geophysicist named Marion Hubbert began contemplating the idea that oil was a finite source that needed to be measured. Using three different methods in his measurements he concluded that the total volume of oil the Earth held prior to oil usage was 2 trillion barrels. By his estimates, the peak of oil production and use would occur during this present decade, and bring about a crisis of decreasing oil production and increasing demand. Other sources such as the United States Geological survey predict the total volume of oil to be 2.7 trillion barrels, which would delay crisis by a decade. (The current rate of production is 25 billion barrels annually.) The crisis that is spoken of is an oil-driven world war and oil-dependent economies crashing with permanent and deadly repercussions.

Oil as we know it can be replaced by other fossil fuels and natural resources such as "heavy oil," oil sands, shale oil, coal, natural gas, and methane hydrate. However, these all have finite quantities and often cause even more environmental damage than does oil. Alternative methods and resources include: nuclear fusion, nuclear fission, breeder reactors, cold fusion, solar cells in geocentric orbit, PV arrays, hydrogen fuel cells, and hydro and wind –induced power.

While this issue of weaning society off of fossil fuel is being discussed and researched, the environment is continuing to suffer. The primary culprit is carbon dioxide that living beings themselves exhale as waste. Carbon dioxide is a greenhouse gas, along with methane, ozone, nitrous oxide, and chloroflurocarbons. In short, greenhouse gases block energy radiating off the earth from passing out of the atmosphere, sustaining a comfortable ambient temperature that can sustain life. As greenhouse gases increase in volume, more infrared radiation is maintained within the earth's atmosphere, causing global warming. With global warming comes the melting of the polar ice caps (one of the primary sources of reflection of radiation), which in turn threatens the habitat of wildlife in associated regions, reduces salinity of the oceans, and raises sea levels. Various methods have been researched which could possibly stop and reverse global warming; these include: blocking radiation from the sun via parasol in orbit between sun and earth, burying CO_2 in former oil fields, liquefying CO_2 on the ocean floor, and making magnesium carbonate bricks.

Despite the many valid and interesting points made by Goodstein, he leaves a lot to be desired. The majority of the book states what would appear to be factual information, but most of it is not explained or properly defended in a way that removes doubt. For example, he states that an increase in greenhouse gases causes global warming, but also includes the fact that increased air moisture/cloud cover and effects on Thermohaline flows may actually cool the earth's atmosphere. And if cloud cover reduces radiation striking the earth and global warming, why is cloud seeding not a possibility in lowering atmospheric temperature? When describing the possibility of cold fusion as an energy source, he states that in 1989 a five week cold fusion frenzy ended by complete disregarding cold fusion as an energy source. Why? He mentions copious alternative energy sources, but then discredits each one as impossible, leaving no defined solution to the problem of oil and environmental crisis.

At the conclusion of his account, Goodstein makes it clear that the only hope for a reversal of our current fate is some future invention or discovery. If all problems were resolved by hoping for future solutions, nothing would be solved. A proactive approach by developed nations is vital to developing a renewable resource that is safe, cost-effective, and dependable. No matter the price to be paid today, it will be dwarfed by the price of ignoring the issues that currently threaten the well-being and existence of the coming generation.

3.2 "Renewable Energy: Progress and Prospects." by Samuel F. Baldwin

Though the modern world is principally powered by nonrenewable energy sources, there are current methods used to harness renewable sources. However, these are not necessarily contemporary means of supplying power, for even the Industrial Revolution began using water wheels, windmills, and biomass fuels. The benefits of renewable energy sources are manifold, with the most obvious being health and safety, lower reliance on oil from political hotbeds, and economic gain. The most prevalent renewable energy technologies (RETs) today, in terms of research and development, are solar photovoltaic technology, wind energy, and biomass consumption.

In 2000, photovoltaic technologies (solar energy) accounted for 0.07 quads of energy out of a total U.S. consumption of 98.5 quads. Solar photons are converted to useful energy using a device which separates electron-hole pairs and generating a current collected with an external circuit. There are various ways to accomplish this feat, primarily crystalline silicone, thin films, high-efficiency cells, and dye-sensitized cells. There are also various obstacles ion accomplishing high efficient cells, including mismatches in solar photon and material bandgap spectrums, optical losses, and resistance in the metal-semiconductor interface. (As of April 2002, the most efficient laboratory solar cell achieved 24.7% efficiency).

Another challenge facing the solar energy industry is the decreasing supply of low-cost materials. Presently, solar panel modules consist primarily of polycrystalline silicone discarded by the semiconductor industry. Supply of these materials will not be able to sustain demand as solar modules gain in efficiency and popularity. One method of reducing polycrystalline silicone consumption would be to focus on thin film technology, which uses cadmium telluride, copper indium diselenide and other alloys. These alloys are situated as micrometer thick layers on glass or steel sheets, trapping and converting photons to produce current. Currently, thin film technologies account for 13% of photovoltaic power production.

At the present state, wind energy is still in developmental stages. In the past 20 years, wind energy production has grown from 50 kilowatts per unit to 900 kilowatts per unit. European countries are leading the way with wind energy, with many countries offering tax incentives to use it. The actual wind turbine used to harness wind energy is subject to many strong forces due to wind causing lateral pressures that must be4 accounted for in design. Early designs didn't design for these forces and therefore did not last long and ultimately failed. For wind power to become a more viable option in the future, more work needs to be done to design a more efficient system. For this new efficient system new materials and design features must be included. For dependable energy from wind, more accurate weather forecasts must also be developed. If these issues are dealt with, wind energy could potentially be of great use in the future.

Biorefineries are one of the most promising ways of providing alternative energy. There are two categories, biochemical and thermochemical. The biochemical refineries use an enzymatic process that breaks cellulose down into its component sugars. These sugars are then fermented and ethanol is produced. This means that it is possible to use waste cellulose materials (corn stalks, for example) to provide energy for society. The problem with this method is that these enzymatic processes are very timeconsuming; genetic engineers are currently researching ways to make this process cheaper, as well as faster.

The thermochemical biorefineries use a gasification process on a biomass. The hot gas which is produced is cleaned and used as combustible fuel in a turbine/gas generator. A 7 MW electrical system in Varnamo, Sweden has been in testing for around 5 years with this type of generator. A larger 60 MW capacity generator has been produced and is being tested in Burlington, Vermont. A way to make a small-scale system is being researched so that it may be possible for farmers and homeowners to make use of this type of energy resource.

During the oil crisis of the 1970's, society expected there to be an increase in renewable energy resources. Although, once the crisis was over and the financial burdens of creating new energy sources were realized, there wasn't as much of a demand for alternative energy sources. It is much cheaper to use the fossil fuels instead of investing in new, potentially risky alternative energy.

The initial cost of alternative energy may be higher, however it is not being considered that wind and solar energy is impervious to price increases. With their gradual integration into society, the cost of alternative energy sources will decrease. Many of them are expected to be competitive with coal over the next decade.

Most of the energy demand in the future will come from developing countries. A large number are already using photovoltaic technology, which provides energy for domestic uses in rural areas. Soon, wind energy will be implemented in these small communities to provide energy for larger scale areas.

4. Nonrenewable Energy Resources

4.1 Introduction

From the onset of the Industrial Revolution, the global economy has been primarily powered by fossil fuels. The advancement of industry since that time has caused an exponential increase in demand for these non-renewable resources. Currently, fossil fuels are used for 82.9% of international energy production: oil – 34.9%, coal – 23.5%, and natural gas – 21.2%.[3]

Over the past half-century, geophysicists and energy-related organizations have attempted to predict how long fossil fuels will provide the means for energy production. The following analysis makes similar predictions based on current reserves and consumption rates.

4.2 Oil

4.2.1 Introduction

Ever since oil became an essential resource in the production of energy, geophysicists and like-minded experts have attempted to pinpoint a numerical value for worldwide oil reserves. The motivation behind such attempts is obvious enough for this information is crucial in predicting the longevity of an oil-reliant economy and society. However, after decades of measurements and predictions, it is still unknown what oil remains undiscovered beneath the earth's surface.

4.2.2 Reserves

Since the 1940s, the postulated amount of ultimate world oil recovery has more than tripled in size. In Figure 1 (taken from a USGS presentation), it is evident that two independent studies conducted in the 1940s concluded that the total amount of oil ever contained within the earth was 600 billion barrels. Before 1960, another study determined that ultimate oil recovery would total 2 trillion barrels. From 1959 to the present, the consensus among experts is that 2 trillion barrels is a relatively accurate number. The most interesting information contained in this graph is the estimates from the year 2000. The USGS estimates that there is a 95% chance of ultimate recovery totaling 2.248 trillion barrels and a 5% chance of that total rising to 3.896 trillion barrels.[4]

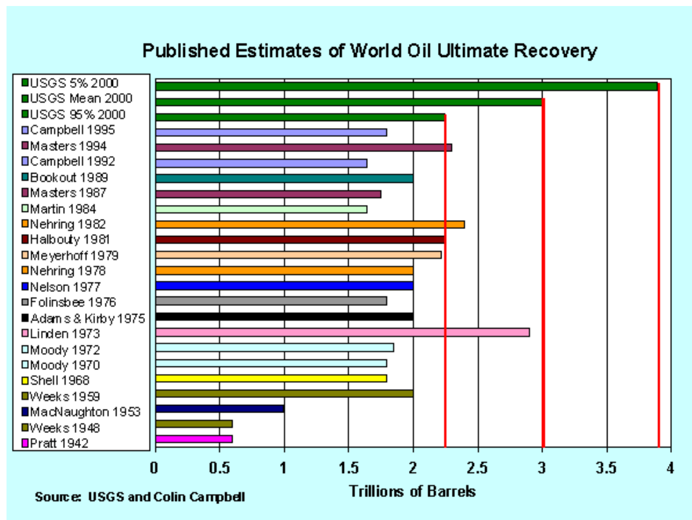

Figure 1: Past predictions of ultimate world oil recovery *

Just as past estimates on total oil recovery have varied, current proven oil reserves also vary depending on the source. The Oil & Gas Journal[5] reports 1,213.1 billion barrels, the World Oil[6] publication reports 1,034.7 billion barrels, and the BP 2004 Statistical Review of World Energy[7] reports 1,147.7 billion barrels. The principle difference between the Oil & Gas Journal and World Oil reports was the amount of proven oil reserves in Canada. The Oil & Gas Journal stated that Canada contained 180.0 billion barrels in oil reserves (which would make Canada second only to Saudi Arabia in total oil reserves), while World Oil reported only 5.5 billion barrels. The Oil & Gas Journal explained that the 180.0 billion barrels was comprised of 5.2 billion barrels of conventional crude oil and 174.8 billion barrels of bitumen. Bitumen is a tar-like substance that can be easily converted into oil.

Using the three estimations of proven oil reserves, 1213.1 billion barrels, 1034.7 billion barrels, and 1147.7 billion barrels, a mean and standard deviation value was produced equal to 1131.8 ± 90.3 billion barrels. This approximation is used in following calculations.

** Refer to Citation of Figures on page 90.*

4.2.3 Production and Consumption

When attempting to determine how long oil will last before reserves dry up, the only logical method would be to regard past production and consumption records and look for a mathematical representation of the data. In Figure 2 below, oil production numbers from 1960 to 2003 are shown. [8] The relationship between time and production is fairly linear save for the period of the 1970s. It was during this decade that oil production reached a peak in Trinidad, Romania, Iran, Libya, Indonesia, and the United States.

To show consumption versus production, data was taken from the Department of Energy's International Energy Annual Report for the years 1970 to 2003.[9] The comparison between consumption and production is shown in Figure 3. It is immediately evident that consumption essentially runs parallel to production. However, the question is posed, how could consumption be higher than production? At first, this would appear to be impossible, because oil must be produced before it is consumed. (The levels of consumption have been confirmed as higher than production by three independent sources.) The most logical explanation for such a relationship would be that production is measured in terms of crude oil and consumption is measured in terms of petroleum. Consumption also accounts for ethanol/bio-diesel additives to oil and petroleum.

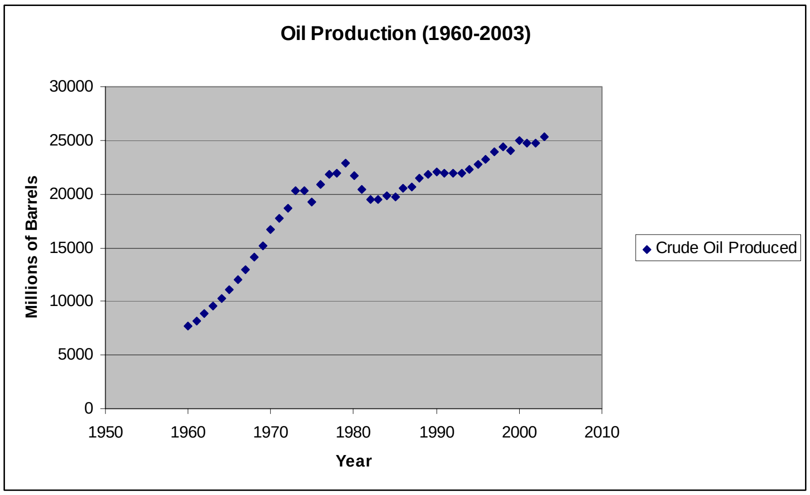

Figure 2: World oil production (1960-2003) *

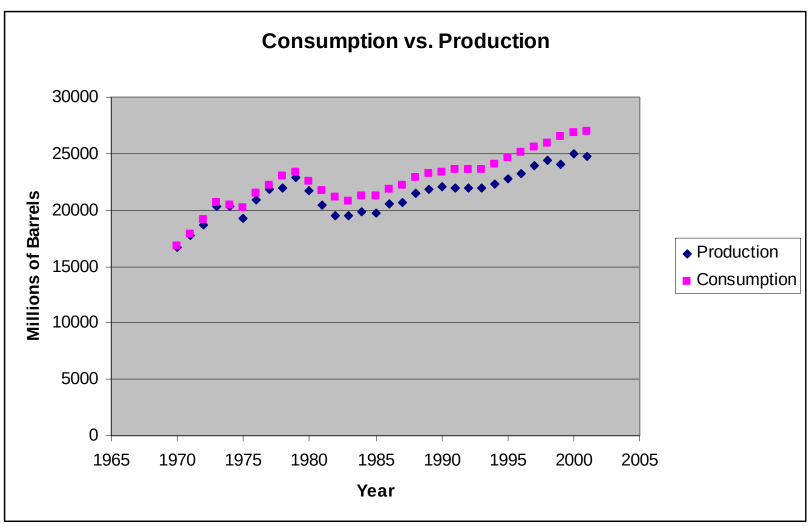

Figure 3: World Oil Consumption vs. Production (1970 - 2003) *

4.2.4 Predictions

The process of predicting future oil production and consumption, relative to declining oil supply is somewhat complicated. In Figures 4-6, the oil production numbers (in millions of barrels per year) are shown for the periods: 1960-2003; 1970-2003; and 1983-2003. For each of the graphs, a linear regression line was produced with its associated r-squared value. (The closer the R^2 value is to 1.0, the more accurate the regression line fits the associated data.)

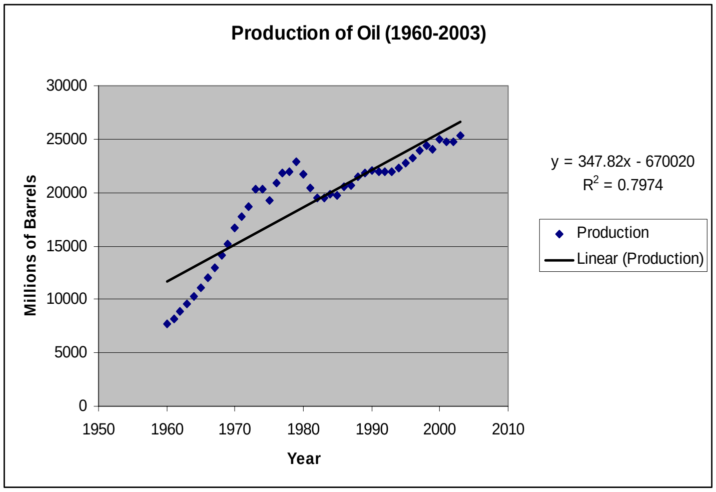

Figure 4: Linear regression of oil production (1960-2003) *

For the first two graphs, the linear regression lines are not very accurate in representing the data within the graph (R^2 = 0.7974 and R^2 = 0.7318, respectively). However, if just data from the past 20 years is shown, a highly accurate regression line can be produced which approximates the upward trend in oil production (R^2 = 0.9598). The equation for this linear regression line is: y = 286.19x – 547907. (The method used to determine the linear regression line values is shown in Appendix A.)

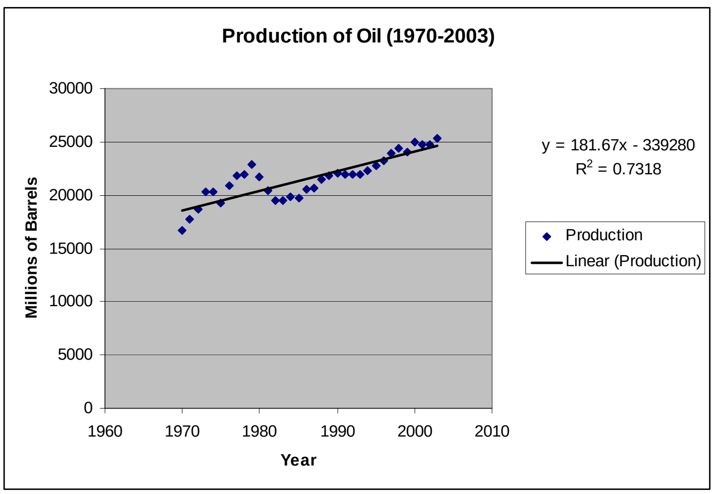

Figure 5: Linear regression of oil production (1970-2003) *

Using the above equation, and the approximation of proven world oil reserves (1131.8 ± 90.3 billion barrels), oil longevity predictions were made. Based on the mean current oil reserve estimates, all available oil will be consumed by the year 2040. Applying the standard deviation of oil reserves, oil

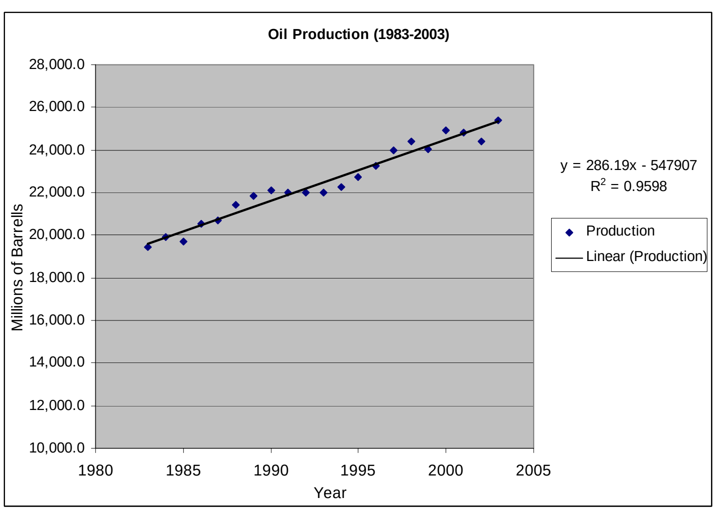

Figure 6: Linear regression of oil production (1983-2003) *

exhaustion could occur between 2038 and 2042.

One important element which has not been included in this calculation is the amount of oil currently undiscovered. If USGS undiscovered resource predictions are correct, there is a 95% chance of 394.3 billion barrels of oil still undetected beneath the earths crust.[10] Adding this amount to the current oil reserves (394.3 + 1131.8 = 1526.1billion barrels) extends oil use to sometime between 2048 and 2052. Figure 7 shows the predicted decreasing oil reserves, according to the various current oil reserves predictions. The lower three lines correspond to the 1131.8 ± 90.3 billion barrels reserve estimation. The top three lines correspond to the 1526.1 ± 90.3 billion barrels reserve estimation.

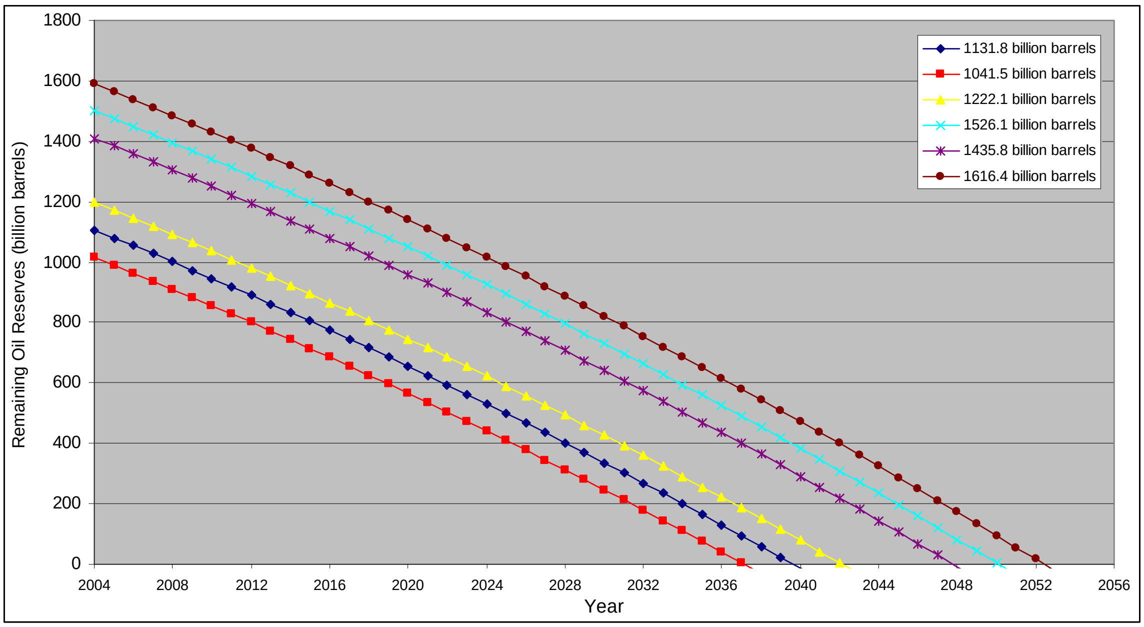

Figure 7: Oil reserve predictions

To state the above predictions without including any error analysis would preposterous. The primary source of error, other than the uncertainty surrounding remaining oil reserves, lies in the prediction of future oil production/consumption. The future oil production figures used in this analysis were based on the linear regression relationship of oil production data from 1983-2003. To determine the possible error of the linear regression line, the standard error of the line was calculated to be 173.22. (The calculation is shown in Appendix A.) By applying this standard error to the linear regression line, the effects on final oil longevity are shown in Figure 8, using the current reserve figure of 1131.8 billion barrels.

Figure 8: Oil predictions, applying standard error to analysis

After applying the standard error to the linear regression line, it is evident that this error does not result in much of a deviation in oil reserve predictions. Therefore, the linear regression line is a very accurate representation of the oil production trends over the last 20 years.

4.2.5 Conclusion

Based on this analysis, oil reserves will be exhausted within fifty years, occurring anytime between 2038 and 2052. The effect of this situation will occur well before oil reserves actually disappear, as price inflation will grow exponentially as resources become sparse. As oil reserves are depleted, there will be a drastic increase in coal and natural gas consumption. The onset of an oil crisis will place huge stresses on U.S. political relations with oil-producing countries, far beyond the severely tenuous current situation in Iraq. Without question, it is imperative that renewable energy sources be researched, developed, and implemented before the impending oil crisis paralyzes this nation, and other oil-dependent countries.

4.3 Natural Gas

4.3.1 Introduction

Natural gas is a form of fossil fuel that occurs naturally, and can be harnessed and used to produce energy. It occurs at a lower depth of both coal and oil, and is therefore needed to be drilled out at deep depths. The distribution of this nonrenewable resource is worldwide, with concentrations in Eastern Europe and the Middle East.

4.3.2 Reserves

The worldwide reserve of natural gas is consistently growing, as more deposits are being discovered and more drilling is done. In 2004 the worldwide reserve totaled over 6000 trillion cubic feet.

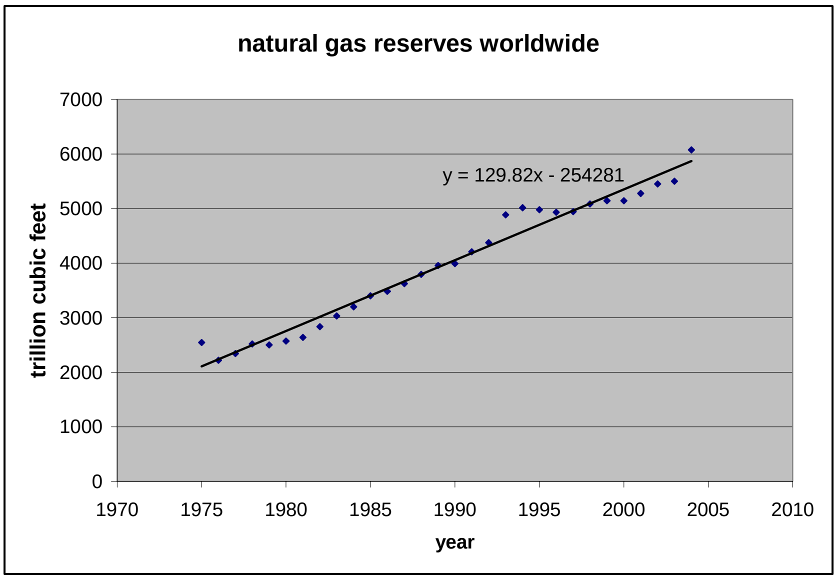

Figure 9: Natural Gas Reserves *

Since 1975 the reserve has continued to grow at a more or less consistent rate. In 1975 the reserve was a bit over 2000 trillion cubic feet, and has continued to rise roughly 4000 trillion cubic feet in the past 30 years. This reserve will continue to grow, until it reaches its maximum, when the bulk of the natural gas deposits have been found.[11]

4.3.3 Production & Consumption

Along with the growing reserve, the production of natural gas has continued to grow over time as well. In 2003 the worldwide production of natural gas was about 90 trillion cubic feet.

However, this number is less significant, because the growing reserve size accommodates more production, and lessens the effect of the growing production. [12] The consumption of natural gas has been growing as well. It has grown from under 40 trillion cubic feet to over 80 trillion cubic feet in the last 30 years, doubling over that time. [13] This trend has also been mostly linear, with a slight decline in consumption rates happening as of the last ten years.

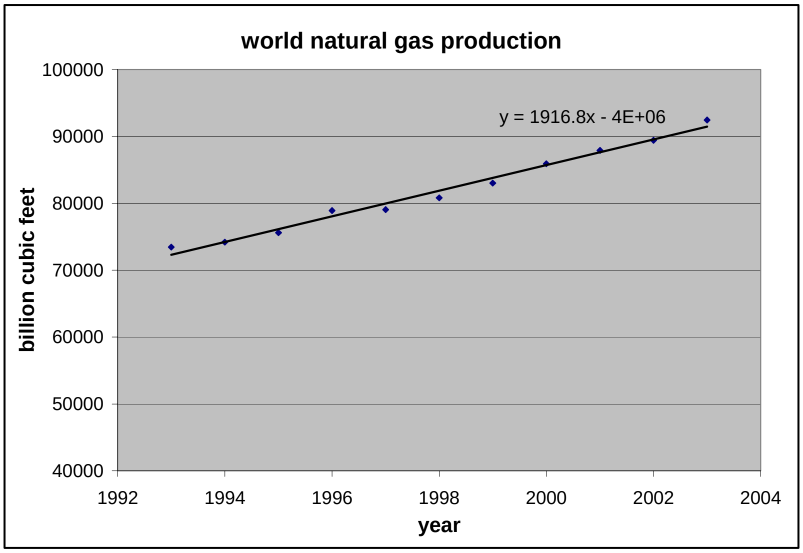

Figure 10: Natural Gas Production *

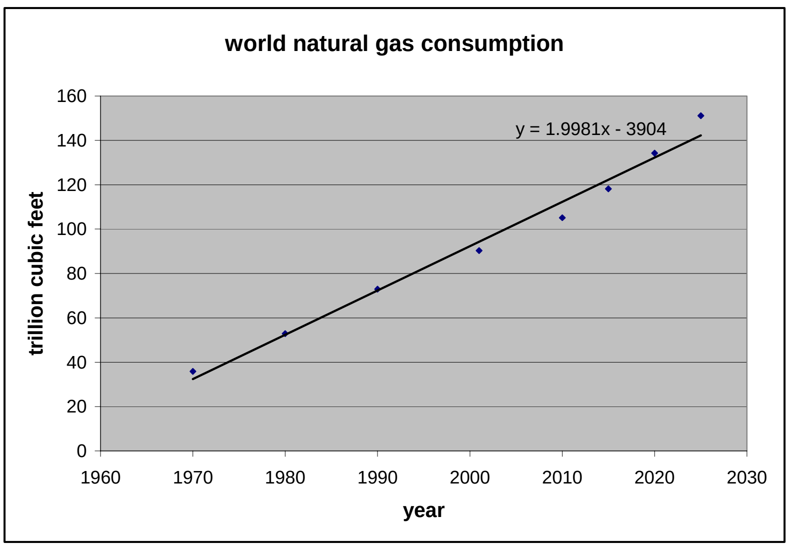

Figure 11: Natural Gas Consumption *

4.3.4 Predictions

Both the values for consumption and production of natural gas have mirrored each other, with consumption depending on production. As more oil is produced, more will be consumed. Estimates as to what consumption/production rate will be in the future is somewhat difficult to predict. Some predictions also state that nearly 200 more years worth of gas is available for drilling in undesirable places at a higher cost. [14] As this figure shows, with the current reserves we have now and the predicted reserves that are not yet drilled or found we will have natural gas to use until 2048.

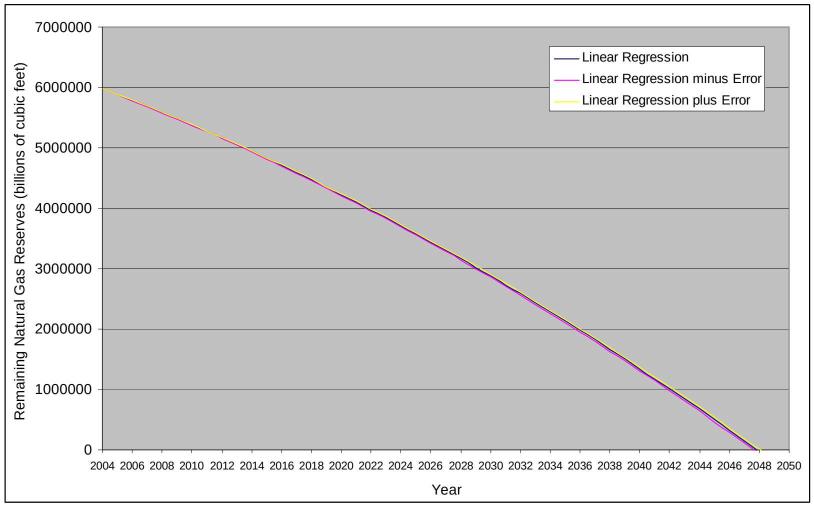

Figure 12: Natural Gas Reserve Predictions

4.3.5 Conclusion

Although natural gas is a viable option to produce energy, it is also a non-renewable resource, and will someday be exhausted. Along with coal and oil, natural gas is a major source or energy both in the United States and worldwide. As the reserves or natural gas deplete, more issues will be brought into play. Since the reserves are spread out all over the world, and are under many countries' land, new political struggles will arise once the demand of natural gas catches up with the supply. The prediction we made is that natural gas will run out in 2048.

4.4 Coal

4.4.1 Introduction

Of the three most commonly used fossil fuels used today, coal is a major contributor to electricity production (37% overall) around the world. It is formed between rocks due to large amounts of pressure, heat, and microbial action. It is considered a sedimentary, carbon-based organic rock consisting of carbon, hydrogen and oxygen.[15]

Coal is generally thought to have been the remains of ancient vegetation that existed in swamps or peat bogs. Over many thousands of years, through tectonic movement, these swamps and bogs were buried and compressed inside the earth's crust. As they were buried, they experienced high temperatures and extreme pressures, causing substantial changes in the chemical and physical makeup of the material. This material eventually turned into the coal that is used today.

The initial swamp and peat bogs were first transformed into brown coal, or lignite, also known as a low organic maturity coal types. Millions of years of compression and high heat eventually matured the material into the sub-bituminous range coal. The next stage of development is the bituminous, or hard coal, stage. Progressing through time, with the right conditions, the bituminous coal will transform into anthracite, the final product.

Softer coals, or coals still in its first stages of transformation, are 'low rank' coals. They have a higher moisture level and low carbon content; therefore they do not produce as much energy. Harder coals in the later stages of development are 'high rank,' corresponding to lower moisture levels, high carbon content and higher energy content.[16]

4.4.2 Reserves, Production & Consumption

According to the Energy Information Association, the world is estimated to contain 1083.259

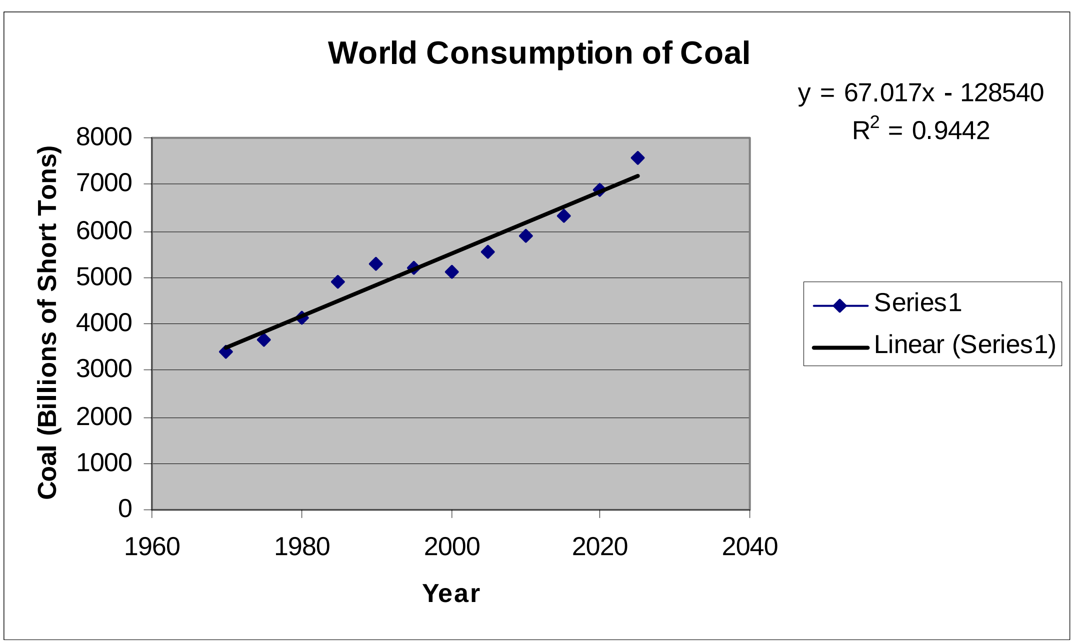

Figure 13: World consumption of coal *

billion short tons of coal.[17] Figure 1 represents the production rate from 1970 to 2003; it is assumed that the production rate is approximately equivalent to the consumption rate. Using the linear equation for the average of these data, the production/consumption rates were predicted into 2025.

4.4.3 Predictions

Using this information, it is estimated that these reserves will last approximately 112 years, (the year 2117) at current consumption rates, as represented in Figure 2. Although it is generally thought that

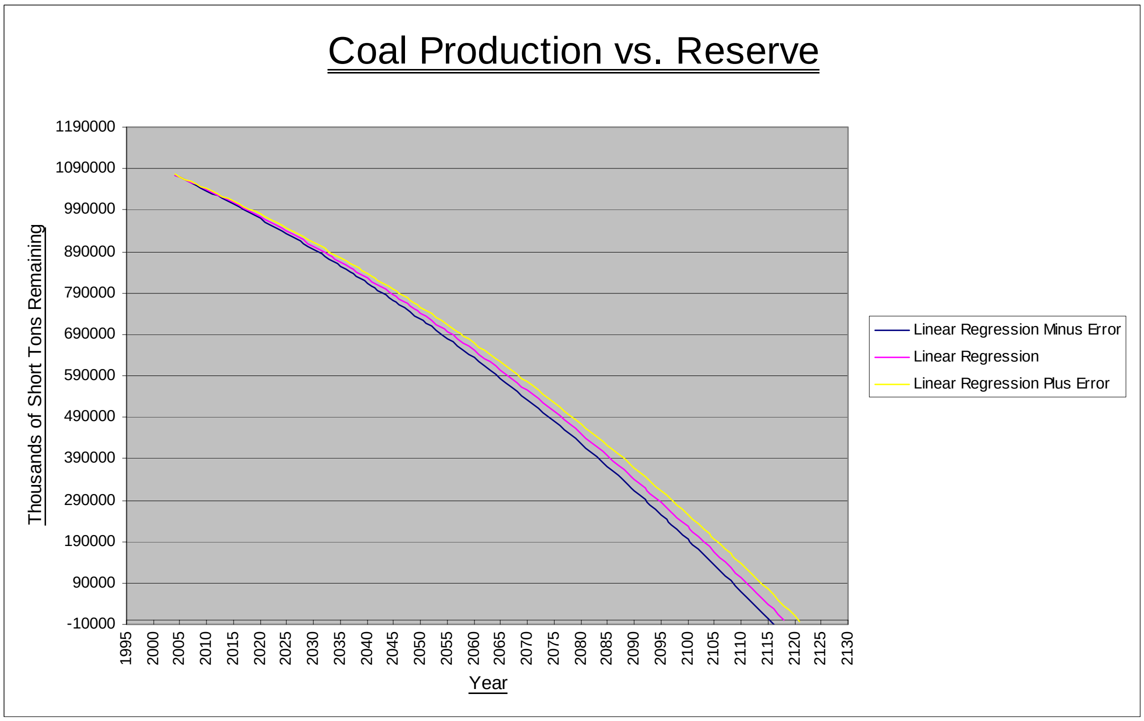

Figure 14: Predicted Coal Reserves

our coal resources may last for a long time, in reality, the estimated 112 years is not accurate. There are many factors which will affect the length of time in which it will take to completely exhaust the world's coal resources. When the other fossil fuels are used up, there will most likely be a large increase in coal production and consumption; this will cause the resources to be used up much faster than previously determined.

4.4.4 Conclusion

There is research currently going on in order to make the burning of coal more efficient and cleaner. Perhaps with the passing of time, new technologies will make this process more efficient, therefore extending the lifetime of our resources. With continuing research, we are continually expanding our technological capabilities regarding alternative energies. Although it is doubtful that coal burning will stop altogether, it would be ideal to replace as much coal production as possible with renewable resources.

5. Renewable Energy Resources

5.1 Introduction

The replacement of fossil fuel-generated energy with renewable energy systems is inevitable as nonrenewable resource reserves dwindle and disappear. Though the adoption and implementation of renewable energy systems will require huge financial commitments and various scientific breakthroughs, it is indeed a blessing in disguise. If fossil fuels were unlimited and there was no incentive to switch to a renewable resource, the condition of the environment would eventually decrease to uninhabitable levels. In the following discussion, wind energy, hydropower, biomass energy, and solar power are all analyzed. The primary emphasis is placed on solar energy, due to the many possibilities that exist for this type of renewable energy resource.

5.2 Wind Energy

5.2.1 Introduction

For hundreds of years, people have been harnessing wind to use as an energy source. Windmills were built in order to pump water, or to grind grain for centuries. Today, wind is being considered, and used, as a reliable and clean energy source.

5.2.2 Mechanics of Wind Turbines

Turbines poised on top of towers are used to harness wind energy. These towers can be 100 feet tall or more, and usually are placed on high ground. The less turbulent and faster winds are able to flow freely through the turbines at high elevations. These turbines are in the form of a propeller, generally with two or three blades. As the wind blows into the blade, a pocket of low-pressure air forms on the downward side of the blade. This air pocket pulls the blade toward it, causing the blades to turn, or lift. This lift force is much stronger than drag forces, or the wind's force against the front side of the blade. The lift and drag forces cause the system to spin as a propeller; the turning shaft is connected to a generator, where electricity is produced.[18]

These wind turbines are used as stand-alone systems, connected into an electric power grid; some are combined with a photovoltaic system. A number of wind turbines are often placed together to form a wind plant or a wind farm. This method is used for large-scale sources of energy and is currently providing power to customers around the country.

Single stand-alone wind turbines are normally used to pump water or for communication purposes. Some are used in small-scale, remote areas to supplement the electricity needs of residential or agricultural areas.

5.2.3 Advantages and Disadvantages

There are many advantages, as well as disadvantages regarding the use of wind energy. It is a clean way to produce energy, due to the fact that it creates no emissions or harmful substances. These turbines are domestic; they are presumably manufactured, located, and operated in the United States. The wind supply is also assumed to be abundant. The wind supply cannot be exhausted or used up; it is created due to the heating of the atmosphere by the sun, the Earth's rotation, and the irregularities of Earth's surface terrain. [19]

Wind energy is one of the lowest-priced renewable energy technologies available; it ranges between 4 and 6 cents per kWh. Of course, the prices depend on the wind resource, and the project financing of the system in question. In rural areas, wind turbines are often used on farms and ranches. This not only provides energy to the owner, but they can rent out their land to a wind power plant owner to bring in extra income. The actual wind tower does not occupy very much land.[20]

Unfortunately, as with most alternative energy sources, the initial investment in one of these systems is much higher than that of a conventional fossil-fueled generator. Depending on how energetic the site is regarding wind forces, the wind farm may not produce enough energy to be cost competitive. These wind sites are often in rural areas, far away from metropolitan areas that have a higher demand for power.

Another disadvantage involves the fact that wind is not constant; therefore it will not always be generating electricity. There is no way to store the wind energy, unless batteries are implemented.

The environmental impact of wind turbines is relatively small, compared to conventional power plants. The blades can be noisy, they aren't necessarily aesthetically pleasing, and there have been reports of birds flying into the blades. Most of these problems have been greatly reduced, or solved through development of new technologies.[21]

5.2.4 Area Feasibility Analysis

Suitable wind areas are assumed to cover approximately 6% of the land in the United States; these areas have the potential to supply around one and a half times the consumption of electricity in the United States. Wind resources are labeled in wind power classes from 1 to 7; each class stands for a range of mean wind power density, or the equivalent mean speed at the specified height aboveground. A class 4 or greater area is suitable with advanced wind turbine development. Class 3 areas are potentially suitable for future technology, and class 2 areas are marginal. Class 1 is not suitable for the development of wind energy systems.[22]

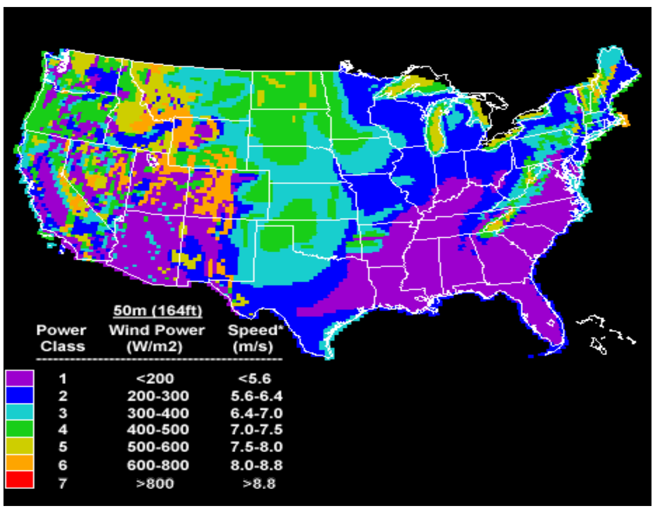

Figure 15: Annual Wind Power Resource and Wind Power Classes *

By comparing the average wind power and speeds in Worcester Massachusetts to the Power Class requirements, it appears as though it would fall into the Class 1 category.

Wind Speeds and Density for Worcester, Massachusetts.		
	Avg. Wind Speed (m/s)	Avg. Wind Power Density (W/m2)
30 meters Annual	4.9	
50 meters Annual	5.3	163
70 meters Annual	5.7	
100 meters Annual	6.2	
50 meters Spring	5.6	171
50 meters Summer	4.4	83
50 meters Fall	5.1	152
50 meters Winter	6.2	245

Table 1: Massachusetts Wind Speeds and Density #

Refer to Citation of Tables on page 95.

5.2.5 Cape Cod Wind Project

Off the coast of Cape Cod, Massachusetts, a large-scale wind farm project, dubbed Cape Wind, is being planned and will be constructed in 2006. It is estimated that it will supply three quarters of the amount of energy currently being used on the Cape. Very strong winds are estimated to produce the entire amount of energy being consumed by Cape Cod, or more. The usage of the wind turbines' electricity will occur mainly on the Cape; when the wind blows, the generated electricity will go into the grid and follow through the path of 'least resistance,' meaning it will flow to the nearest users. At times when more electricity than is being used on the Cape enters the grid, it will extend out to other areas. A company by the name of La Capra, a consulting firm, has calculated the average savings of approximately $25 million per year for the New England electricity market, with the use of this new wind farm.[23]

There are many environmental benefits associated with this project. It is estimated to replace up to 113 million gallons of oil per year. When it is fully operational and providing electricity, it will eliminate 4,642 tons of sulfur dioxide, 120 tons of carbon monoxide, 1,566 tons of nitrous oxides, more than a million tons of greenhouse gases, and 448 tons of particulates from being emitted into the air per year.[24]

5.2.6 Conclusion

Wind energy is proving to be a very reliable and suitable resource for energy in the United States. Its environmental benefits are astounding, and the cost effectiveness is going down with new developments and technology. Since the Earth's wind resources will never be exhausted, and there are no dangerous by-products associated with its energy production, it may be a very feasible fossil-fuel-replacement in the years to come.

5.3 Hydro Power

5.3.1 Introduction

The harnessing of water flow and conversion to electricity is called hydropower. Hydropower is the most used form of renewable energy in the United States, with more that 2000 operating hydropower plants. These 2000+ plants in the U.S. make up for 7% of our energy production, while worldwide hydropower accounts for more that 20% of produced electricity.[25] Water flow has been being harnessed to do work for along time now. Water wheels were used in previous societies to grind meal and other foods. Hydropower is taking that work to the next step and creating electrical power from the natural gravitational flow of water.

5.3.2 Process of Energy Conversion

Hydropower plants use a fundamentally simple process for converting the flow into energy. The flow of a river is blocked or dammed, and within this dam is a small channel for the water to flow through. By making the water flow through a smaller opening the pressure and speed at which the water flows through the opening is far greater than that of the natural running river. The water that is being dammed up raises the hydraulic head, adding pressure to the water flowing through the hole and making it flow even quicker. This concentrated and pressurized water flow is then sent through a turbine. This turbine is in turn connected to a generator that produces electrical current.[26]

To break down the process in which this power is converted will explain the exact process in which hydroelectric power is formed. As stated previously the water first is dammed up, creating a reservoir upstream from the dam. The water then flows through the intake valve into the penstock, a channel that will carry the water through the dam. In the penstock the water flow can be controlled by a gate the can be raised and lowered to change the dimensions of the penstock.[27] The water is then passed through a turbine which is turned at high revolutions from the flow. This turbine is connected to a generator that contains large magnets inside of it. When revolved these magnets create an alternating electrical current (AC). In an onsite powerhouse, this AC current is then subjected to a transformer and changed to a higher voltage current. The energy is then sent through electrical wires to the main grid where it is distributed to the public.[28]

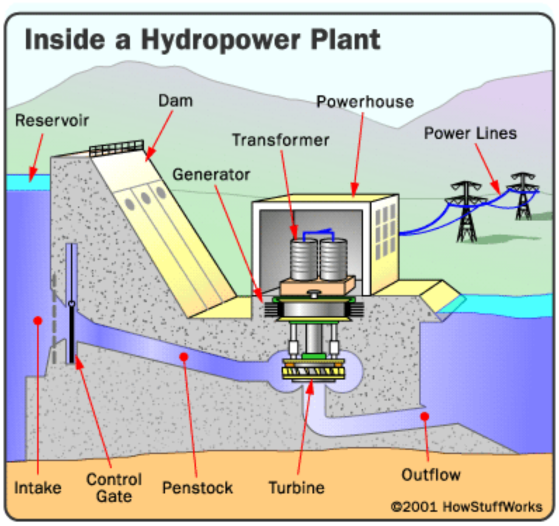

Figure 16: Inside A Hydropower Plant *

5.3.3 Advantages

One main proponent of hydropower is the fact that it is relatively cost efficient and clean for the environment. No waste is left behind in the wake of this power conversion, unlike the burning of fossil fuels or using nuclear means. It also does not produce any greenhouse gasses, and therefore does not contribute to the greenhouse effect as other energy sources do. The cost to convert the electricity is also less than other forms of power conversion. As this graph shows the cost to produce hydroelectric power is less than other forms of conversion, accruing costs only in operation and maintenance of the facility. Hydropower's cost at 0.85 cents per KWh is significantly lower than that of other means, and is only 40% of the total cost of power transformed from fossil fuels. [29]

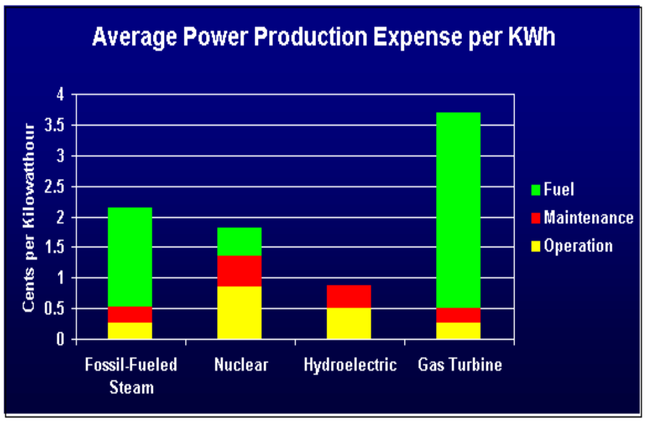

Figure 10: Average Cost per KWh *

5.3.4 Limitations

Because of the low impact and the cost efficiency of hydropower it is desirable to use this form of power conversion where it can be applied, but it is limited by natural means and relies on constant water flow. This can be a problem because in many parts of the country water in a valuable resource and there is hardly enough to go around. The Colorado River, for example, barely reaches the Mexican border anymore, because nearly all of its water is used by farmers and others by the time it reaches Mexico. Other limitations arise in the planning of a dam and reservoir. When dams are made the land in which the reservoir will occupy will often have to displace people from their land. This often results in the moving of whole towns, and therefore is very impacting on many people's lives.

5.3.5 Conclusion

Hydropower proves to be very beneficial in the efficient production of usable energy. Through the process of damming a water flow clean usable energy can be produced, but this production is limited by the number of rivers, and river valley large enough to house a dam and the resulting reservoir. As of today the United States produces about 7% of its energy through hydroelectric means. [30] Hydropower is an important and efficient contributor to overall power production in the U.S., but due to its limitations further alternative energy production methods will be needed to compliment hydropower for a future of clean renewable energy.

5.4 Biomass Energy

5.4.1 Introduction

The principle dilemma concerning fossil fuel consumption for energy production is the ever decreasing supply of available resources. The development of fossil fuels through decomposition and compression of biological matter takes far too long to even remotely replenish the resources that have been used. One possible solution to this problem is the processing and consumption of biological matter and waste, defined as biomass, for energy production. Essentially, this method consumes biological fuels before they become fossil fuels. Altogether, biomass energy production now accounts for approximately 3-4% of total U.S. energy consumption.

Biomass materials can be converted to and consumed in solid, liquid, and gaseous form, much like fossil fuels. The most prolonged and most common use of biomass for energy production has been the burning of wood for cooking and heating needs. In an electricity generating situation, the biomass is burned, producing steam which turns an electricity producing turbine. The argument could be posed that biomass consumption is not a valid solution because the associated production of carbon dioxide is similar to that created by fossil fuel consumption. However, the biomass that is used for energy production is replenished by new growth of trees, plants, etc, which consume carbon dioxide to sustain life. If biomass materials were produced and consumed at an equivalent rate, the net emission of carbon dioxide would be essentially inconsequential.[31]

5.4.2 Pyrolysis

As mentioned previously, biomass materials can be used for energy production in ways other than simple combustion of solid materials. Pyrolysis and gasification of biomass is the conversion of solid biological matter into liquid and gaseous form, respectively. Pyrolysis is performed by heating biomass to approximately 550^{o}C in an oxygen-free environment, producing a solid, char, and a mixture of gases, including hydrogen, carbon monoxide, and methane. The gases are then condensed to form a liquid bio-oil which can be used for electricity generation. There are various techniques used for pyrolysis, such as bubbling fluid beds, circulating beds, cyclonic reactors, and ablative reactors. [32] Depending on the technique used, the bio-oil produced through pyrolysis varies between 40-75% of the input biomass, with 10-20% of the biomass being converted into char, and 10-30% of the biomass being converted to incondensable gas.[33]

In Figure 1 below, a type of cyclonic reactor, known as the PyRos reactor, is shown. This design is said to eliminate problems associated with pyrolysis char production. When char is present in the produced bio-oil, repolymerization occurs, increasing the viscosity of the oil and making it unusable in energy production applications. In the PyRos reactor shown below, a rotating filter is used to capture micron char particles present in the oil vapor. The pure oil vapor then is funneled to a condensation device, which separates bio-oil from incondensable gas.[34]

Liquefied biomass materials are the building blocks of ethanol and biodiesel fuels. Ethanol is usually made by combining ground feedstock, such as grain or barley, heat (120-150 degrees Celsius), alpha-amylase and gluco-amylase enzymes, and yeast. The resulting mixture is then subject to distillation, dehydration, and denaturing before it can be used as a gasoline additive.[35] The amount of ethanol production in the United States has increased significantly over the past three years: 2.1 billion gallons in 2002, 2.8 billion gallons in 2003, and ~ 3.3 billion gallons in 2004. The U.S. currently has the capability to produce approximately 3.5 billion gallons of ethanol per year. [36]

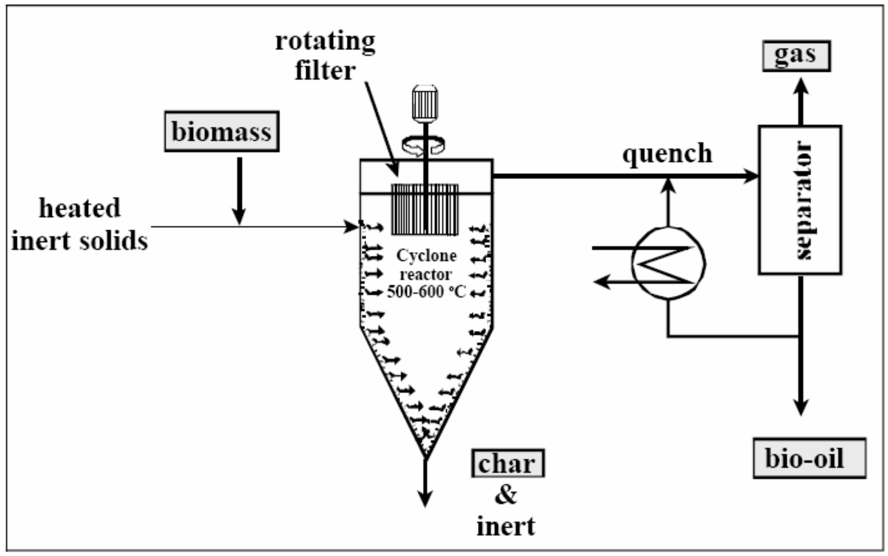

Figure 11: Pyros cyclonic reactor *

Biodiesel is produced by the processing of animal fat or various types of vegetable oils, including rapsead and soybean oils. These biomass materials undergo transesterification with alcohol and methanol to remove glycerin.[37] The resulting methyl ester is biodiesel. Unlike ethanol, which is used as a octane-increasing gasoline additive, biodiesel can be used as both an additive or an independent fuel source. In Figure 2, the advantages of biodiesel versus a biodiesel-petroleum mixture is evident.[38] (B20 represents a fuel comprised of 20% biodiesel and 80% petroleum diesel.) In 2002, 15 million gallons of biodiesel was consumed in the U.S. alone.

BIODIESEL REDUCES EMISSIONS

EMISSION	B100	B20
Carbon monoxide	-43.2%	-12.6%
Hydrocarbons	-56.3%	-11.0%
Particulates	-55.4%	-18.0%
Nitrogen oxides	+5.8%	+1.2%
Air toxics	-60%-90%	-12%-20%
Mutagenicity	-80%-90%	-20%

Figure 19: Biodiesel environmental benefits *

5.4.3 Gasification

The method of gasification is quite similar to pyrolysis, except that the condensation device is eliminated. The intense heating of biomass, with a limited amount of oxygen, forms a mixture of gas consisting primarily of carbon monoxide and hydrogen, referred to as synthesis gas. Synthesis gas is highly efficient for combustion energy production because it readily mixes with oxygen. The uses of synthesis gas correspond to natural gas uses.

5.4.4 Disadvantages

The disadvantages related to biomass energy production somewhat parallel those related to fossil fuels. First, the process of converting bio-matter into usable energy resources and the subsequent consumption of those resources both cause pollution. Secondly, the expense of energy and/or financial resources for biomass re-growth after consumption may result in a net loss. Unlike other renewable energy resources, biomass requires significant maintenance to ensure its renew-ability.[39]

5.4.5 Conclusion

The use of biomass for energy production is critical for partially alleviating the enormous demand for petroleum and for utilizing otherwise useless biological waste. However, it is evident that biomass is not the ultimate solution to the impending nonrenewable energy shortage. Biomass energy consumption is harmful to the already delicate environment, and it requires too much time and human interaction for replenishment to be relied on as primary energy source.

5.5 Solar Energy

5.5.1 Introduction

The most abundant source of renewable energy is solar energy. There are various ways in which solar energy is collected and used. The most common applications of solar energy are electricity production and heat generation. The main deterrent to widespread application of solar energy systems is the low efficiency of solar panels and the exorbitant cost associated with implementation. However, as research and development of these systems continue, efficiencies increase, and costs drop, the potential of solar energy is without limits.

5.5.2 Semiconductor Properties

The principle of photovoltaic technology is the conversion solar radiation into electrical current. Semi-conductive materials serve as the mechanism by which these conversions occur. Semiconductors are simply insulators with a narrow 'forbidden' band gap. At low temperatures, no conduction occurs, but as temperature increases, energized electrons leave the valence band and enter the conduction band.

The semiconductor most often used in photovoltaic and other technologies is silicon. A silicon atom has four valence electrons which covalently bond to neighboring silicon atoms to form a silicon crystal. At certain temperature levels, electrons in the covalent bonds can obtain sufficient energy to break free, leaving a hole. Freed electrons are considered to be within the conduction band. The width of the forbidden band gap in the semiconductor is equal to the minimum energy required to release an electron from a covalent bond.

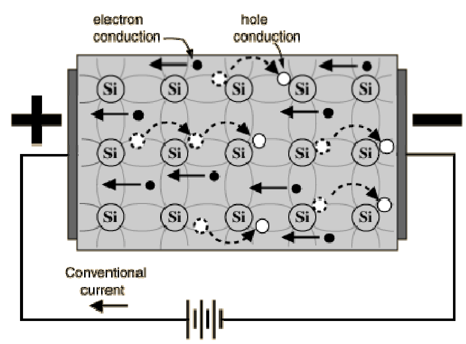

Figure 20: Voltage-induced current flow *

Current can be induced by applying a voltage to the semiconductor. The current consists of the movement of freed electrons and the apparent movement of holes, as neighboring electrons fill vacant bonds, as shown in Figure 20.[40] In order to modify the properties of a semiconductor, various impurities can be added to the silicon crystal. These impurities can either be trivalent impurities (group III elements) such as boron, aluminum, or gallium, or pentavalent impurities (group V elements) such as antimony, arsenic, or phosphorous.[41] These two types of impurities are shown in Figure 21. The trivalent elements are used as "p-type" semiconductors by producing electron deficiencies (holes). The pentavelent elements produce "n-type" semiconductors by added extra electrons.

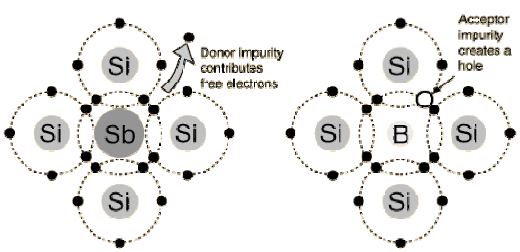

Figure 21: Antimony (pentavalent) and boron (trivalent) doping of silicon *

The n-type materials cause extra electron energy levels which can easily be excited into the conduction band. The p-type materials cause extra holes in the band gap which allow for easy excitation of valence band electrons.[42] This is shown in Figure 22.

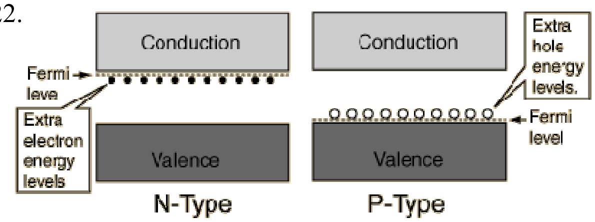

Figure 22: N-type and P-type energy levels *

5.5.3 Solar Radiation

Most of the energy produced by the sun lies within a $2x10^{-7}$ to $4x10^{-6}$ meter wavelength range, which corresponds closely to the visible light region. As shown in Figure 4, each wavelength has a corresponding frequency and photon energy level. The smaller the wavelength, the greater the frequency and energy, and vice versa. Solar cells react differently to different radiation wavelengths. For radiation energy levels too far outside the visible light region, solar cells cannot produce current (electricity), instead converting the energy into heat.[43]

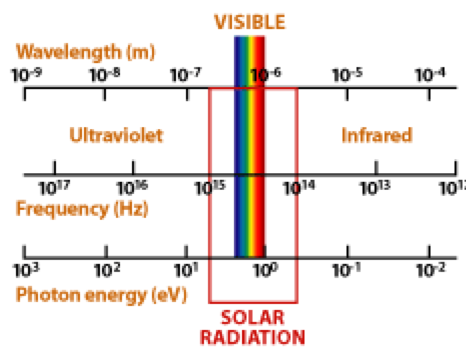

Figure 23: Solar radiation relative to visible light *

The earth's distance from the sun and atmospheric properties significantly reduce the amount of energy that actually reaches the earth's surface. At the outer edge of the earth's atmosphere, the radiant energy has been measured at ~1367 W/m^2 and is labeled as the solar constant or air mass zero radiation. Passing through the earth's atmosphere, the sunlight is attenuated by at least 30% due to Rayleigh scattering, absorption, and reflection. Under clear conditions, the most important determinant in the amount of energy reaching the earth's surface is the air mass. Optical air mass describes the point when the sun is directly overhead, and the radiation at the earth's surface is denoted as air mass one radiation. Air mass can be calculated using the two methods shown below:[44]

1. Air mass = $1/(\cos\theta)$ (θ = sun's angle to overhead)
2. Air mass = $\sqrt{[1 + (s/h)^2]}$ (s = length of shadow; h = height of vertical structure)

Air mass one (AM1) radiation has been calculated at ~1000W/m^2. As the sun moves lower in the sky, the air mass increases, reducing the radiation energy striking the earth's surface. In order to calculate the average amount of radiation reaching the earth's surface throughout a clear day, AM1.5 radiation measurements have been taken. (AM1.5 indicates that the path of light through the atmosphere is 1.5 times as long as optical air mass.) These measurements have determined AM1.5 radiation to be ~ 970 W/m^2. However, this value is standardized at 1000W/m^2.[45]

5.5.4 Photovoltaic Performance

In order to determine how much power a solar cell will produce, current-voltage relationships are measured to determine the electrical characteristics of a given photovoltaic cell. Tests are conducted by subjecting the cell to a constant level of light, maintaining a constant temperature, applying variable levels of resistance, and measuring the amount of produced current. The maximum current produced would be the short-circuit current and the maximum voltage produced would be the open-circuit voltage. However, with a short circuit, voltage is zero, and with an open circuit, current is zero. Therefore, the power produced, which is simply the produce of current and voltage, is each case would be zero.

Using a current-voltage curve, it is relatively easy to determine which product of current and voltage would yield the maximum power output. The maximum power represents the maximum efficiency of a given solar cell. The conversion efficiency of a solar cell is simply the percentage of solar energy which is converted to electric current. This efficiency is affected by a number of factors, namely: wavelength or radiation, recombination of electrons and holes, natural resistance, temperature, reflection, and electrical resistance.[46]

5.5.5 Photovoltaic Efficiencies

The efficiency of a photovoltaic cell is simply determined by measuring the amount of electric energy (kWh) produced when cell is subject to a known quantity of solar energy. The research and development of photovoltaics began in the 1950s, with an initial efficiency 6% by the end of 1954. Efficiencies rose quite rapidly until 1960, when 14% was achieved. [47] Strangely enough, the ensuing twenty years yield little, if any, progress in photovoltaic development. In 1983, 18% efficiency was achieved,

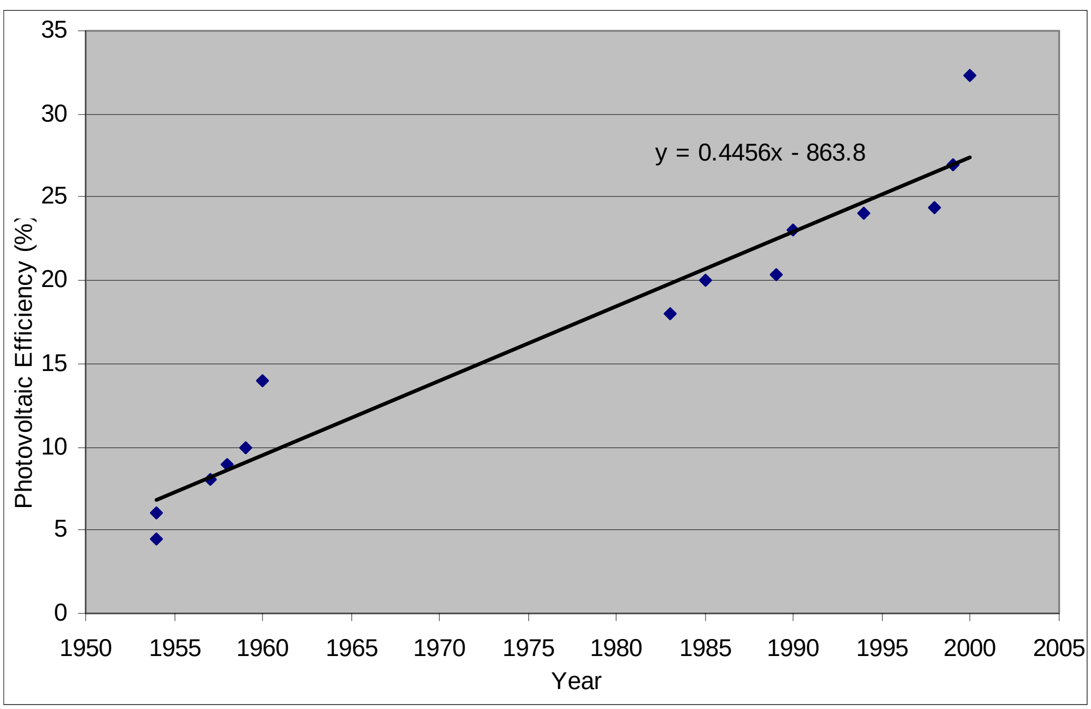

Figure 24: Timeline of photovoltaic efficiencies *

sparking a rather consistent trend of increasing efficiencies over the next twenty years. The evolution of photovoltaic efficiency is shown in Figure 5.[48] The highest recorded efficiency for conventional, silicon photovoltaics is 32.3%, achieved by Spectrolab, Inc. in 2000.[49]

The linear regression line shown in Figure 5 is a rough estimate of increasing photovoltaic efficiencies from 1954 to 2000. Using this approximation, photovoltaic efficiencies will reach 49.68% by 2050. However, it must be expressed that the photovoltaic efficiencies discussed here relate to ideal laboratory testing. For example, though current laboratory efficiencies have surpassed 30%, solar panels on the market have not exceeded 17% efficiency. If this trend continues, by 2050, salable photovoltaics will have efficiencies of approximately 26%.

5.5.6 Photovoltaic Prices

As mentioned in the introduction, the other primary limitation of solar energy systems, besides efficiency, is expense. The price of energy per kWh from nonrenewable resource power generation facilities is much cheaper than the price associated with solar energy systems. However, grid-supplied kWh prices are rather steadily increasing, as shown in Figure 6. As nonrenewable energy resources become increasingly limited, it can be expected, that kWh prices will jump substantially. Based on the data shown below, kWh prices have increased at a rate of 3.08% per year since 1978.

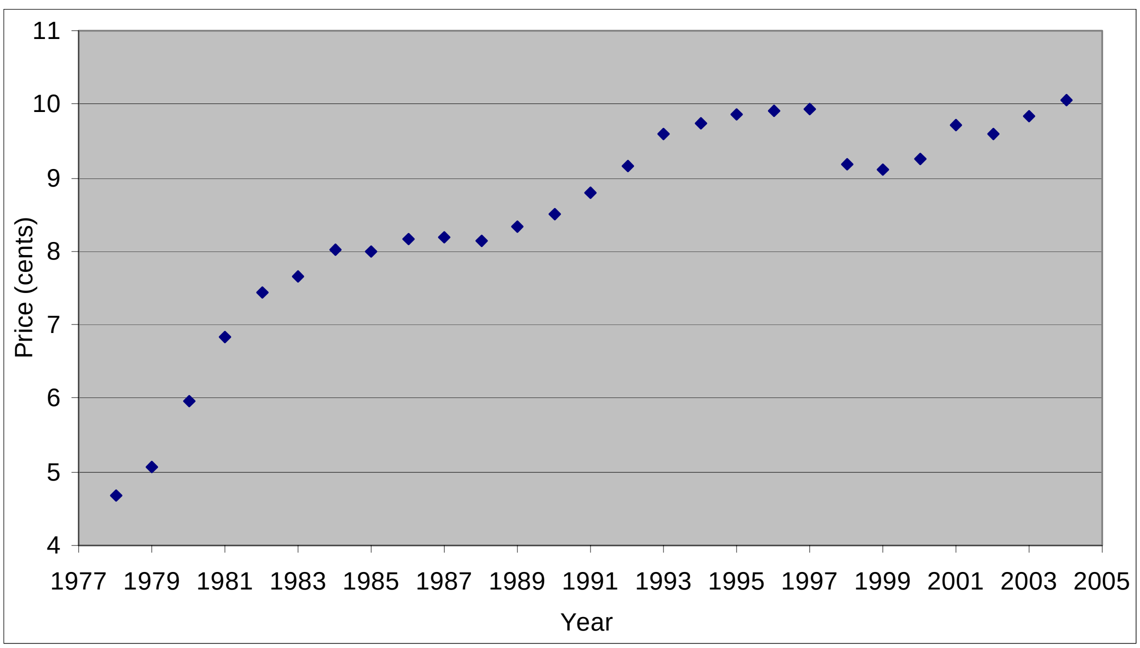

Figure 25: kWh prices (1978-2004)

The price of photovoltaics per watt is shown in Figure 7. From October 2000 to January 2005, photovoltaic module prices have dropped from $5.91/watt to $5.04/watt.[50] Using this data, the mean and standard deviation for years 2001-2004 were calculated, as shown in Figure 8. By determining the linear regression estimation related to annual photovoltaic module prices, projections could be made concerning future prices.

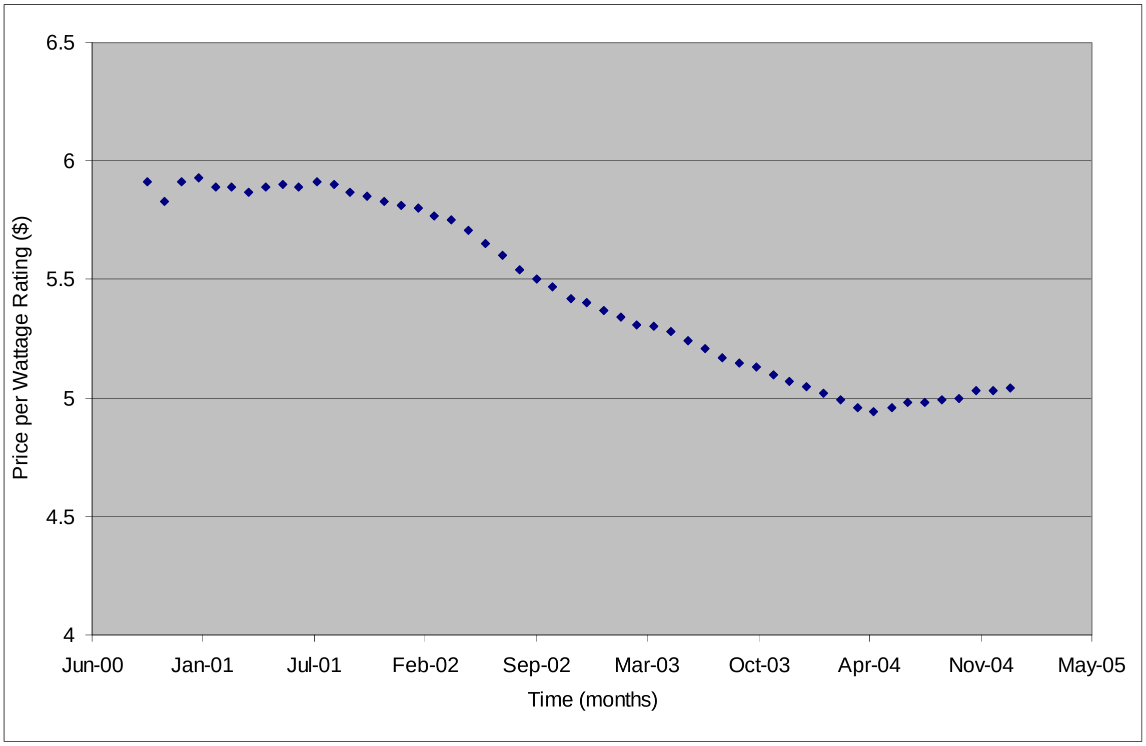

Figure 26: Photovoltaic module prices per watt (October 2000 – January 2005) *

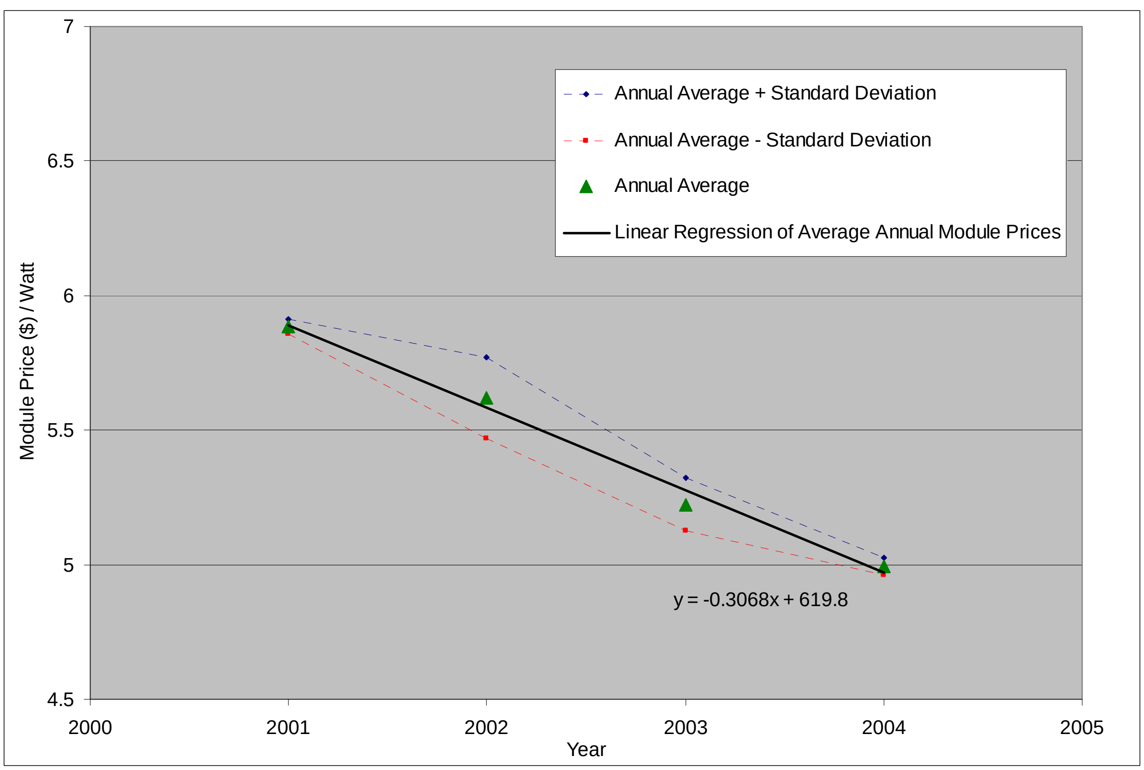

Figure 27: Photovoltaic module prices per year

Using the linear regression relationship, it is expected that photovoltaic prices will drop to $3.13/watt in 2010, $1.59/watt in 2015, and $0.06/watt in 2020. It is difficult to compare module prices (per watt) to grid-supplied electricity prices (per kWh) because the module prices are based on power output while electricity prices are based on energy output. The kWh production of a panel is relative to its location and orientation. If the panel is located in an environment near the Equator, where solar radiation exposure is optimal, the kWh production of the panel is very high. Also, the cost associated with the solar energy production is not limited only to the module price. The relationship between watt rating for a panel and kWh output will be explained in detail further on, in the WPI solar power system discussion. In terms of the data presented here, the only certain conclusions which can be made are that increasing grid-supplied kWh prices and decreasing solar module costs will steadily enhance the potential of widespread solar power system implementation.

5.5.7 Concentrating Solar Power Systems

There are many different ways in which solar power can be collected and used to provide electricity. There are three divisions of Concentrating Solar Power Plants: Trough systems, Dish/Engine systems, and Power Towers. These types of systems are being researched and tested currently. They each consist of different configurations of mirrors, used to convert the sun's energy into extremely high-temperature heat. This captured heat is then used to heat water for a steam-powered turbine. This method is a clean, potentially reliable way to generate electricity.

5.5.7.1 Parabolic Trough Systems

It is estimated that if we covered 9% of Nevada (100 square miles) with parabolic trough systems, the electricity created could power the whole country. This method uses rows of trough shaped mirrors, with an oil-filled pipe running down the center. These rows are situated parallel to each other, running from North to South; they rotate to follow the sun as it passes from East to West overhead. An internal computer adjusts the mirrors so they are constantly facing directly into the sun. The rays are reflected off the sides of the trough and onto the center pipe. The oil is heated to an extremely high temperature, and it is then used to heat water to power a steam turbine. Each individual trough system can produce up to 80 megawatts of electricity. [51]

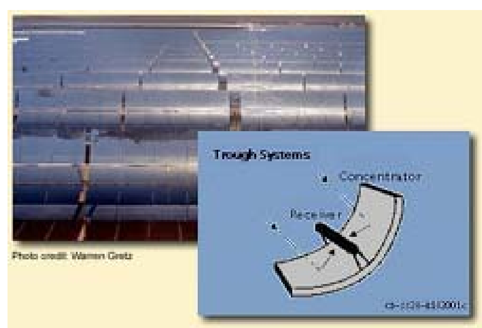

Figure 28: Parabolic Trough System *

5.5.7.2 Power Tower

Another method involves using a tower to collect the sun's rays. These power towers have some sort of heat-retaining fluid inside, in which a field of mirrors is directed towards. The fluid is heated to extremely high temperatures from the sun's energy. It is then used to heat water for a steam-powered turbine, as in the trough system.[52]

Figure 29: Power Tower and Field of Heliostats *

A molten salt fluid mixture is being tested and used in these power tower systems. It is comprised of 60% sodium nitrate, and 40% potassium nitrate. This mixture can retain thermal energy, as opposed to water, which is not as useful for containing heat. [53]

A field of mirrors, called heliostats, is constructed in an area where there is a consistent amount of solar radiation, generally a desert. These heliostats are basically sun tracking mirrors. Inside each mirror is an internal computer that keeps the mirror pointed at the same point on the tower. The computers update every few seconds and adjust the mirror automatically; therefore the sun's energy is constantly reflected onto the tower. [54]

If this hot liquid is stored in an insulated container, for example, a vacuum-insulated container, it can be used at our disposal to power an area when needed. 1000 acres of mirrors can produce 100 megawatts with a single tower and 12 hours of stored energy. This is enough electricity to power 50,000 homes. [55]

Two such plants have already been tested already, Solar One and Solar Two. Solar One, a 10 megawatt plant near Barstow, California produced over 38 million kilowatt-hours of electricity while it was operating between 1982 and 1988. Solar Two used the efficient molten salt method, and it routinely produced electricity during the nighttime and cloudy weather. The tower demonstrated its efficiency when it provided power to a grid for almost an entire week before cloudy weather intervened. Such plants are being considered and planned in countries around the world to provide clean, non fossil-fuel energy.[56]

Figure 30: Power Tower *

5.5.7.3 Dish/Engine System .

The third type of concentrated solar power is a Dish/Engine system. These types of solar energy generators consist of a myriad of mirrors that reflect the sun's rays on to a solar concentrator, where they are "burned" in the power conversion unit to create electricity. [57]

Glass mirrors are used to reflect the sun's rays. They reflect approximately 92% of the energy that hits them, are easy to clean, and relatively inexpensive. These mirrors are focused on the solar concentrator; it directs the energy onto a very small area so that the energy is condensed, and more efficiently used. A power conversion unit receives the concentrated energy; it is then transferred to a generator. A power conversion unit is usually comprised of a combination of tubes containing cooling fluid, such as helium or hydrogen. The fluid has a dual purpose of being a heat transfer medium, and it is also used as a working fluid in the engine. Individual units range from 9 to 25 kilowatts in produced electricity.[58]

Figure 31: Dish/Engine System A *

What is the cost for these types of power plants? Surprisingly enough, for large-scale power generation (10 megawatt-electric and above), Concentrating Power Technologies are the cheapest type of solar power. Currently,

Figure 32: Dish/Engine System B *

technologies cost between $2 and $3 per watt. This puts the cost of solar power to between 9¢ and 12¢ per kilowatt-hour. Technological advances and using low-cost thermal storage will inevitably allow these Concentrating Solar Power plants to operate for extended hours during the day, and into the night. Advances are predicted to allow solar power to be generated for 4¢–5¢ per kilowatt-hour within the next few decades.[59]

5.5.8 Residential Solar Energy Use

5.5.8.1 Introduction

Harnessing solar radiation has many applications that are applicable to daily life. The energy that is sent from the sun can be utilized in a variety of ways, and can be used to heat water and air to aid daily living, in addition to being converted to electricity.

5.5.8.2 Water Heater Design

One method for using solar energy is solar water heating. Sunlight is used to heat up water, which in this case is being used as a transfer fluid to transfer the heated water to provide heat for buildings. Solar water heaters use a flat plate design that collects solar energy on an absorptive surface which is in contact with water, and thus heats the water up. Solar water heaters can be categorized into two types, one type combines the heating and storage functions in a single unit, and the other uses separate units for heating and storage.[60]

One key feature in water heater design is using a material for the surface of the collector that will not reflect any light, maximizing the amount of solar energy collected. Other key design features include creating an airtight environment inside the collection area, as well as strong sides and proper lateral sheer support to withstand wind loads. When designing a water heater system thought should be put into the elevation on both the collector and the storage tank. If the tank is mounted higher that the collector than thermo-siphon flow made be used to circulate the water, but if the storage tank is located lower than the collection area a pump must be incorporated into the design to provide flow in the system. These systems can be designed with much flexibility. A crude system can consist only of a tank and a collection area, while more advanced systems can incorporate an electric pump and pressure regulation of the line pressure in the system. On larger, commercial systems larger collection surface area is employed and large pumps are used to circulate the water. One must pay particular attention to the connections between the collection panels and the lines feeding the system. A very small air bleed can disrupt the whole system and greatly reduce its efficiency. Auxiliary heating methods can be added to the system for backup; this can be achieved by incorporating an electrical heater in the storage tank. To overcome dangers involved with the system freezing in cold or temperate climates a heat exchanger can be used. This is often achieved by using a fluid of water and ethylene glycol, which operates at a higher temp than water, to maintain a temperature above freezing. [61]

5.5.8.3 Location Dependency

As with other methods of harnessing solar energy the amount of water that can be heated using this method per unit-area is dependant on the location of the system in relation to the Earth, along with the positioning of the unit toward the sun. One direct consequence of solar water heating is the reduction of conventional energy use. This graph is an accurate representation of the energy savings in certain locations due to solar water heating. As expected, the more sunlight an area receives the more energy is saved.

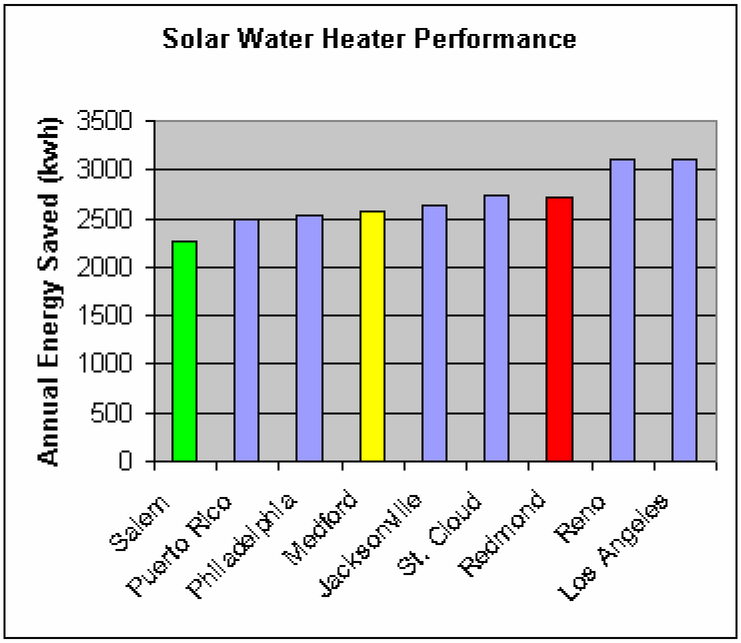

Figure 33: Solar Water Heater Performance *

5.5.8.4 Solar Heating Methods

Solar energy can also be used to heat air, and thus reduce energy consumption used for heating homes and other buildings greatly. Two main design systems for accomplishing the heating of air have been developed. One is a design that uses a fluid as a heat exchanger, and the other uses direct transfer of heat to the area.

The first design uses a liquid that is heated and stored in a tank. The heated liquid from the tank is then circulated around a closed circuit that contains an air heating device such as baseboard heating. This system is very similar to conventional forced hot water home heating systems, except the water is heated by solar means instead of a hot water heater.[62] The second type, not used nearly as often, is a system in which the radiation collector is located in contact with the area that is being heated. This system utilizes convection to heat the air in the area, and is thus limited as to where the device can be located. In certain conditions the convection method can prove to be very economical and efficient, but most of the time the liquid heating design is more efficient and more accommodating to flexible designs. [63]

5.5.8.5 Massachusetts and California Incentives

In order to push for incorporating renewable energy into the homes of residents, many states are offering tax reductions on the purchase and installation of a solar power system. There are also commercial electric providers who have programs where they will buy the electricity generated from a residential solar system from the home owner. The monetary benefits being offered in Massachusetts and California are compared to find the feasibility of implementing a system into a primary energy source. The incentives for both Massachusetts and California are included in Appendix B.

When compared, the incentives to build a home use solar energy system in California far outweigh those to build one in Massachusetts. The legislation in California includes many more ways to subsidize homeowners building solar energy systems. The incentives for Massachusetts are much more restricting than those in California, and are costly considering the fact that not as much quality sunlight reaches the northeast as does the southwest region of the country. [64]

5.5.8.6 Conclusion

Home uses utilizing solar radiation can dramatically contribute to the reduction of energy use, and subsequently drastically lower conventional energy costs. Using solar energy to heat water and air for everyday use not only aids everyday living, but helps to conserve energy produced by oil and other nonrenewable resources. Other incentives are also offered by the state government to help subsidize the cost of home use solar energy systems.

5.5.9 Solar Power Satellites

5.5.9.1 Introduction

Although it is not commonly accepted by society, Earth is currently facing a looming energy crisis. Our fossil fuels are being used up, and the search for alternative energies is our only option to provide power to an energy-hungry planet.

One of the technologies being researched and considered are Solar Power Satellites. These energy sources are located within Earth's orbit, which eliminates the terrestrial struggle for space. The general theory behind the idea is that these solar collectors will transmit energy back to earth in order for us to integrate it into our current power grids.

There are many concepts that have been devised, and are currently being worked on, in order to design and implement a Solar Power Satellite. Scientists and researchers are trying to come up with a feasible alternative way to provide energy to an increasing demand for power. There are many concepts that have been designed and analyzed, but some of the most potentially feasible include the "MEO Sun Tower," the "GEO Heliostat," and the "Abacus Reflector." Each of these satellites are to orbit the Earth using a Geostationary Orbit.

5.5.9.2 Geostationary Orbit

In 1968, the first geostationary satellite was launched into orbit. Since that time, approximately 600 satellites have been placed in geostationary orbit. Such placement is advantageous because these satellites remain in a fixed position above a certain location on earth at all times. Simply put, these satellites make one full rotation about the earth in 23 hours 56 minutes. The satellites are situated approximately 35800 kilometers above the equator and are therefore subject to minimal restrictive forces. While these satellites are being used, frequent corrections are made to the direction of satellite movement (using thrusters) to ensure that the satellite is in the equatorial plane and moving in the direction of the Earth's rotation. After a period of time, satellites become outdated or unusable and are moved a few hundred kilometers farther away from the earth. These uncontrolled satellites form the geostationary belt. In theory, these satellites would remain in orbit for possibly millions of years. In Figure 1, the geostationary belt is shown as it would look from a fixed location in space.[65]

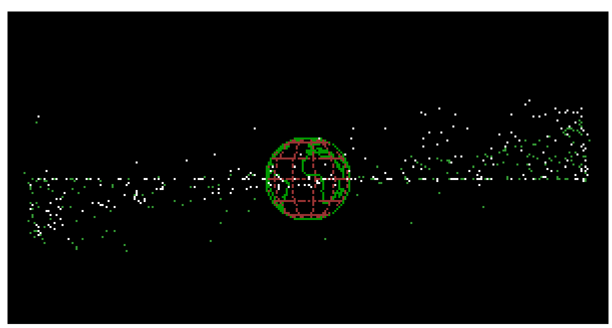

Figure 34: Geostationary Belt *

Once a satellite enters the geostationary belt, its inclination is no longer controlled. Due to gravitational forces of the sun and moon, and effects of the earth's oblateness, the inclination of uncontrolled satellites vary between 0 and 15% over a period of approximately 54 years. In Figure 2, the inclinations of satellites in the geostationary region are shown. The points in the graph that appear to have zero inclination represent controlled satellites

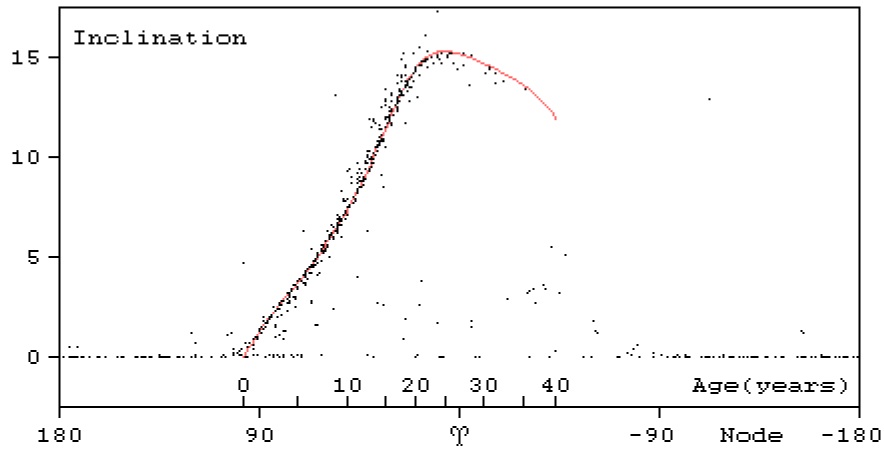

Figure 35: Geostationary satellite inclination angles *

(inclination between 0 and 0.1°). The red curve represents the theoretically calculated curve of the evolution of inclination. The red curve represents the theoretically calculated curve of the evolution of inclination. The points surrounding this curve represent controlled satellites at varying levels of their inclination evolution.[66]

5.5.9.3 MEO Sun Tower

The "MEO Sun Tower" concept involves several inventive approaches to decrease the cost of development, as well as the life cycle cost of maintaining the satellite. The segment will be initially deployed into the Earth's lower orbit, and later it will migrate to an elliptical orbit. It is self-assembling, includes integrated propulsion, and an RF phased array for wireless power transmission.[67]

The satellite will be located at a 12,000 km equatorial orbit. It will cover between +/- 30 degrees of latitude coverage. The system will require a moderate amount of energy storage on Earth, depending on the platform configuration and the specific orbit. Deployment of the satellites will be accomplished using commercial launch services. [68]

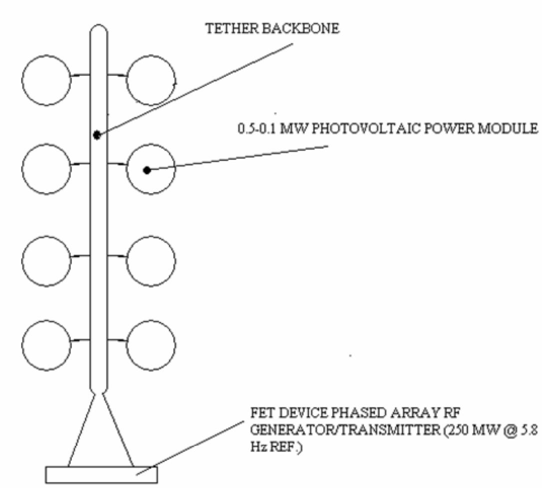

Figure 12: MEO Sun Tower *

The satellite itself is described as an "Earth-pointing sunflower in which the face of the flower is the transmitter array, and the 'leaves' on the stalk are solar collectors."[69]. It is assumed that the concept will transmit at 5.8 GHz from its initial orbit of 1000 kilometers. [70]

5.5.9.4 GEO Heliostat

Similar to the Sun Tower, the GEO Heliostat also has a geostationary orbit involving a system of mirrors that track the sun. The sunlight is reflected onto a single transmitter that sends the energy back to earth. The difference between this system and the Sun Tower is the lack of a long, connecting backbone. This reduces the power management and difficulties involved with the Sun Tower. Although, this system is assumed to have more thermal problems, since the power generation method is assumed to be thermal or photovoltaic. The mirrors do not have a power source, so an alternate integrated electronic propulsion system will be require for orbital rising. [71]

5.5.9.5 Abacus Reflector

The Abacus Reflector Solar Power Satellite concept is another idea that is being considered for implementation. The solar collectors are always facing the sun, which will allow for very little shadowing. The internal solar concentrator uses a shifting lens to provide accommodation for seasonal beta-tracking. It will eliminate the rotational joints between the PV cells and the abacus frame. The frame that supports the lightweight solar concentrators provides structure that will enable robotic maintenance. [72]

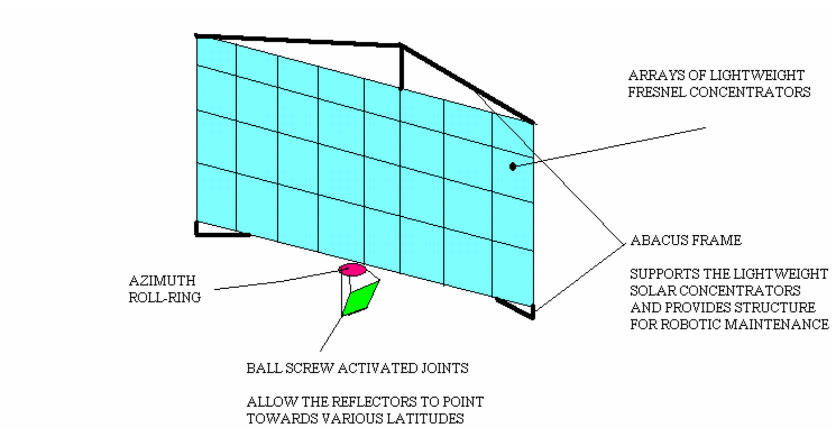

Figure 37: Abacus Reflector *

5.5.9.6 Energy Transmission

Now that we have all of these ideas and concepts of various Solar Power Satellites, how are we supposed to get the energy from space to Earth, in order to distribute it to our power grids? The U.S. Department of Energy and the National Aeronautics and Space Administration developed the original concept. It involved a one-kilometer diameter antenna, located at one end of the satellite. This antenna will transmit microwave energy to a receiving antenna on Earth. The earth's receiving antenna is 10km x 13km, and is elliptically shaped. This receiving rectifying antenna (rectenna) will convert the energy to direct current, which is then distributed throughout our conventional power grids. [73]

Another concept involves the collection and concentration of energy within the satellite, depicted in Figure 3. The energy is then beamed to a marine location in a concentrated laser energy form. The receiving site, or rectenna, uses the incoming energy to split seawater into two components; hydrogen and oxygen. The hydrogen is pressurized, either liquefied and loaded onto tankers for shipment, or passed directly into a pipeline network. These networks would involve facilities used for storing hydrogen in either a liquefied or gaseous form. The hydrogen will then be distributed as needed to consumers.[74]

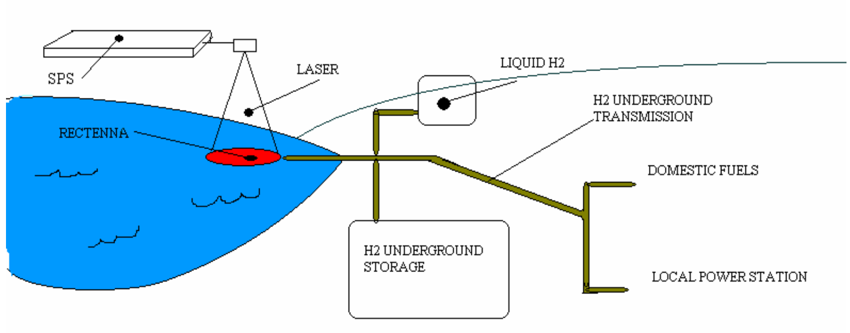

Figure 38: Hydrogen Energy Process *

These are just a few of the many concepts and ideas involving Solar Power Satellites. There are many designs depicting the actual satellite, and the process of getting the energy back to Earth. Unfortunately, due to financial and technological boundaries, these ideas are not very feasible. Until the technology for these satellites goes down in price, and size, these ideas cannot be made a reality.

5.5.9.7 Projected Size and Cost

Currently, with our technological abilities, the satellite would require ten square kilometers of solar cells in order to generate 1 gigawatt of energy on Earth per year. Solar panel efficiency on the market currently is anywhere from 10-17%. In ideal laboratory settings, they are achieving solar cell efficiencies close to 30%.[75]

A report that was released from NASA and the DOE in 1979 described the technology and costs associated with operating an SPS system. They said that the satellite would need to be 21 square miles (6.5 by 3.3 miles), and the surface would be covered with 400 million solar cells. The transmitting antenna on the satellite would be a half-mile in diameter, while the receiving antenna on Earth would require 6 miles in diameter. To get this satellite into space, it would need to be sent up in pieces and assembled while in orbit.[76]

The estimated cost for such a satellite was estimated at $74 billion, and it would take around 30 years until completion. Japan’s Space Development Agency has been planning a project like this one, which will orbit at 36,000 kilometers above Earth. The energy will be transmitted in a laser form to an airship orbiting at a lower altitude of 20 kilometers. From the airship, the energy will be transmitted through ground-based antennas as microwave energy, or through an optical fiber.[77]

5.5.9.8 Disadvantages

There are many disadvantages to constructing a massive solar power satellite in addition to the cost. One of them would include space debris; fragments from other spacecraft, as well as rocks and other objects from outer space. Debris colliding with the satellite can cause anything from small dents and scratches, to serious malfunctions, even explosions. The damage caused to the satellite will cost a significant amount in repair and maintenance costs.[78]

5.5.9.9 Getting the Satellite Into Orbit

One of the most viable ways in order to get these satellites up into orbit would be by the use of an orbital transfer vehicle (OTR). These vehicles would take a piece of the satellite up into space at a time. The International Space Station will have a mass of 454 megatons, and will require 46 construction flights. Comparing that to our satellites with a mass of approximately 20,000 megatons (around 44 times the size of the ISS), it will take an estimated 2024 construction flights in order to complete our satellite. [79]

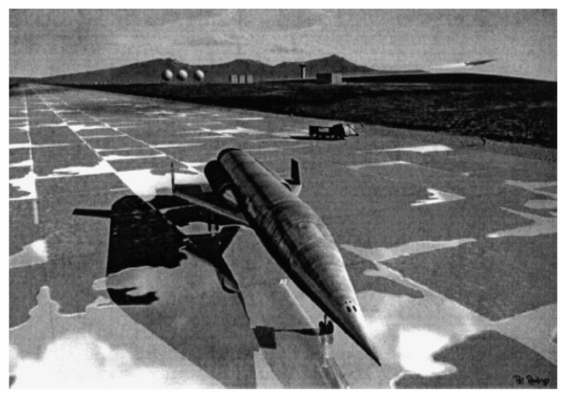

Figure 39: *Argus* Rocket-Based Design *

One of the components involved in getting the satellite into space is the Earth to Orbit (ETO) system. A vehicle, which was designed to be operational by the year 2020, has been considered to be an option in getting these satellites into orbit. The *Argus* rocket-based design was configured for high component reusability, low cost, long life, and a quick turnaround time. One of the designed configurations has been estimated to deliver 40 megatons to an orbit of 300 kilometers above Earth. [80]

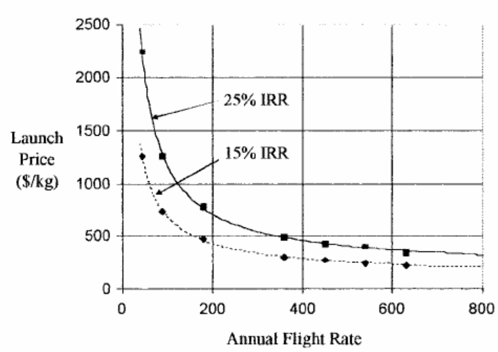

Figure 40: Earth to Orbit Launch Prices *

The cost of a launch will depend on the annual flight rate and the desired internal rate of return (IRR) for the operating company. Assessing the economics of *Argus* showed prices for flight rates ranging anywhere from 45 to 630 flights per year for both 25% IRR and 15% IRR. This information was used to fit a curve that shows the continuous expression for launch prices as a function of the flight rate at 25% and 15% IRR (Figure 5). [81] In order to determine the cost of launching an OTV into space, an equation has been derived in order to predict the expenditure. Where L is the low rate and H is the high rate:

$$LP_{ETO} = L + (H - L)\left[\frac{\text{annual flights}}{450}\right]^{-a}$$

The previous analysis was done under the assumption that one 1.2 Gigawatt capacity satellite would be launched into geostationary orbit every year for 30 years. Using the previously defined equation to find the launch prices, a private Earth to Orbit transportation company would be the one in charge of sending 40 megaton packages into a lower earth orbit. [82]

Concepts have been proposed regarding in-space transportation of the solar power satellites. The propulsive technology involved in the concepts is used to group these concepts. Some of the proposed concepts included nuclear thermal rockets, solar thermal rockets, solar electric propulsion, momentum exchange tethers, and all-chemical rockets. The reusability of these concepts is also used in classifying these systems. Concepts range from disposable to highly reusable. [83]

Number (1)	Item (2)	Mass (kg) (3)
1.0	Solar collectors	1,899
2.0	Body structure	962
3.0	Propulsion	1,362
4.0	Thermal control	14
5.0	Fuel storage	1,998
6.0	Data processing	200
7.0	Navigation sensing/control	89
8.0	Telecom and data	75
9.0	Dry weight margin	990
	Dry Weight	**7,589**
10.0	Reserves and residuals	334
11.0	Propellants	12,427
	Outbound propellants	6,690
	ACS	441
	Extra propellant	5,296
12.0	SSP payload	19,649
	IMLEO	**40,000**

Table 2: *Swarm* Component Weights [#]

There is a long round trip flight time associated with the solar electric propulsion. Due to its low thrust propulsion, the number of trips is restricted; therefore a large fleet size of these would be necessary to transport the satellite into orbit. The nuclear thermal rocket would provide both a high specific impulse and a high thrust; transporting the satellite into space using this concept would require a smaller fleet size. This concept is purposefully overlooked usually, since the use of nuclear power in Earth's orbit is generally not considered an acceptable risk.[84]

There are also expendable OTVs which are being considered to be used as a lightweight, high-performance, low cost transporter. The SEP OTV concept would not involve a long trip timeline, the thrusters and tanks on the SEP would be disassembled at the geostationary orbit; they would be kept on the solar power satellite being constructed. These one-way SEP concepts would need to be mass-produced and involve a very inexpensive launch in order to be competitive with other options.[85]

Swarm, one of the most feasible options in a one-way SEP concept, is prepackaged with its solar power satellite load on the ground. This is more cost effective than the in-space operations involving the loading. The concept is powered by 18 Hall-effect thrusters, and is said to have a high impulse (2,500 s); this would result in low propellant costs. The propellant used is Krypton, it is much more cost effective than the generally used Xenon, and is more widely available. [86]

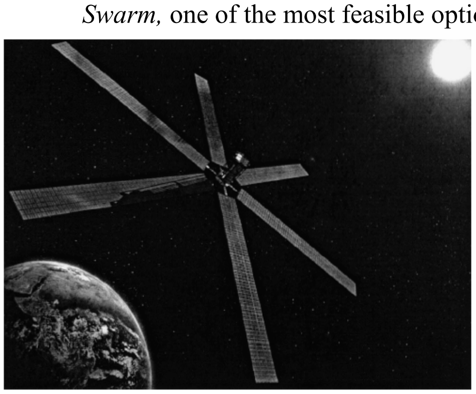

Figure 41: *Swarm* Ascending to Orbit *

Its spiraling trajectory is said to take 116 days to go from lower earth orbit to geostationary orbit, with an initial mass-to-power ratio of 200 kilograms per kilowatt. To reduce the transit time, a higher power level would need to be incorporated, but it would increase the mass of the system. [87]

Swarm will be mass-produced, accumulating large quantities per year in production. The steady-state average unit production cost is calculated by using estimated unit costs for each subsystem. Each vehicle is estimated to cost $12 million, or $1,523 per kilogram of dry mass. The weight of each vehicle is determined in Table 1. [88]

Although this may seem like an extraordinarily large amount of money, it is not too far off from other spacecrafts that are also produced in large quantities.

Krypton and Xenon are the gases that are normally used for electric propulsion. They are expensive, assumed to be about 100 times more expensive than hydrogen or oxygen. Electric propulsion engines require a more expensive propellant, but they also have a higher impulse speed. This higher speed obviously costs more, but it will require a shorter transit time. [89]

5.5.9.10 Social Impact of Solar Power Satellites

It is very important to consider the social and environmental impacts of all of these ideas and concepts regarding Solar Power Satellites. Although the idea may sound very straightforward, there are always other considerations that affect the implementation of such a system to provide energy for our planet.

Since the panels would be outside the Earth's atmosphere on a satellite, they would be more efficient than panels on the Earth's surface. When the sun's rays pass through Earth's atmosphere, energy is lost. This loss of energy accounts for a significantly lower level of solar power that can be produced on Earth's surface. With a Solar Power Satellite in orbit around Earth, much more energy would be able to be harnessed and sent down to Earth This will lead to a reliable, clean source of energy that can replace our current use of fossil fuels.

The energy collected from these satellites will be converted to electricity and sent back to Earth in the form of microwaves, where large rectifying antennas will collect it. This could impact Earth in many ways, but it is impossible to know exactly what would happen as a result from these microwave beams being sent through Earth's atmosphere. There are many theories regarding the results of this scenario.

One of the most popular suspicions is that the beam would not affect society at all, and would pass through the atmosphere unnoticed. Another theory mentions that that the beam would fry the Earth's atmosphere, resulting in devastating effects. There could be cataclysmic global warming and extreme weather effects, or the beam could simply cook humans and animals alike from the inside out.

It is not known what will happen, but using microwave energy appears to be the most viable form of sending the energy back to Earth. Using this energy will result in a high conversion percentage rate back to electricity from the microwave beam.

The collection stations located around the globe would be strategically placed to maximize their collection capabilities while minimizing the effect on society. They would be placed in rural areas, far away from major cities. It would be impossible to completely prevent all human repositioning, and invariably some people will be displaced from their homes. These collection areas would also have to be proven safe, and they will not be allowed to omit any harm energy or substances. With new technologies come new dangers and uncertainties. No short-term or long-term effects have been studied for such a device, so it is hard to determine what effects it will have on the environment, and society.

Assuming that much research was completed and the microwave beam was found to be safe, other effects from the Solar Power Satellite would impact Earth and its inhabitants. The energy supplied from these satellites would be extremely clean, especially when compared to oil or coal burning methods of energy production. With the reduction of oil and coal burning methods, much less pollution would be emitted into Earth's atmosphere. It has been mentioned that the greenhouse effect would begin to reverse. Solar Power Satellites would supply clean energy and thus add to the support of an Earth friendly worldwide power supply, while alleviating the need for a major energy source other than oil.

Each panel that was placed on the solar power satellite would generate about eight times the energy that it would on Earth. This large increase is due both to the lack of atmosphere around the satellite, and the fact that the satellite wouldn't be in darkness at all if placed in geostationary orbit. For example, a 53.8" x 29" panel capable of producing roughly 64 watts on Earth would produce 512 watts in orbit. When the energy is then sent back to Earth as microwave energy, fewer amounts of energy are lost due to atmospheric intervention.

Many different designs for maximizing the energy produced from a Solar Powered Satellite have been developed. Lightweight designs will prove to be the most feasible to transport and assemble in space. Many possible designs have been created using material already in space to assist in the assembly of the Solar Power Satellite. One such design incorporates using material excavated from the moon to create a satellite. Experts have estimated that if used efficiently, over 95% of the satellite could be made from moon rock. However, one setback of this design is the fact that a moon excavation plant would first have to be established. Another design involves fastening panels to the moon and sending the energy back to Earth in a similar fashion as the Solar Power Satellite. A third design calls for capturing a meteor traveling through space, fastening panels to it, and setting in geostationary orbit. Although these designs seem a bit far fetched for the current state of technology, in the future these methods may be feasible, and prove to be more economical than methods current technology permit.

The development and implementation of a solar power satellite system may be one way in which the United States will generate its energy in the future. With this system, nearly eight times the amount of energy would be produced, compared to the Sun. This energy would be clean and lack any harmful side effects, adding to the improvement of the environment and helping to reverse the greenhouse effect. Through research, new methods of energy production such as the Solar Power Satellite will be developed to aid in the need for usable energy. By creating these methods and expanding our ideas on energy production, we will be ready for the future and able to successfully confront the world's diminishing fossil fuel supply.

5.5.10 WPI Solar Power System

5.5.10.1 Introduction

The implementation of solar power systems as a partial or complete replacement of electricity production and consumption has been considered for Worcester Polytechnic Institute (Worcester Campus). The motivation behind this study was to determine the feasibility, in terms of operation and cost, of such a system in order to further examine the potential of solar energy. The social and environmental impact of such a system was also considered.

5.5.10.2 Worcester Solar Radiation

Before exploring the implementation of solar panels, it was necessary to determine the solar radiation present here in Worcester throughout the year. This information was obtained from the 1961-1990 National Solar Radiation Data Base, from which solar radiation recordings for specified locations throughout the United States were readily available.[90] This federal study used fourteen different solar radiation collector devices at each location to determine the amount of kilowatt-hours per square meter per day (kWh/m^2/day) for each month. This unit of measure for radiation means that, for a given location, there are a certain number of hours per day in which a radiation collection device experiences one kilowatt per square meter. For example, 3 kWh/m^2/day indicates that a certain radiation collector experienced 3 hours of kW/m^2 in one day.

Of the fourteen various solar radiation collector devices/orientations that could be used for solar power generation, only four were chosen for the following reasons. The methods for solar radiation collection are comprised of either flat panels or concentrators, which either remain stationary or have sun-tracking systems. For the purposes of this project, stationary flat panel systems with various orientations were analyzed. The concentrator modules and sun-tracking systems were not considered due to expense, complexity of operation, and aesthetic consequence.

The four orientations of these solar panels are: horizontal, south-facing at an angle of latitude minus 15^o, south-facing at an angle of latitude, and south-facing at an angle of latitude plus 15^o. Each of these orientations has associated advantages and disadvantages in terms of solar power generation. In terms of the south-facing orientation of the panels, latitude minus 15^o is optimal during the summer months, when the sun is oriented north of the equator, and latitude plus 15^o is optimal during the winter months, when the sun is oriented south of the equator. (The latitude location of Worcester is 42.27^o.) In Figure 1 below, the Worcester solar radiation, in kWh/m^2/day, for each of these panel orientations is displayed. The actual measured kWh/m2/day values for each orientation are displayed in Table 1. It is evident that there is not one orientation that is overwhelmingly superior to the others, for each panel orientation is optimal for different parts of the year.[91]

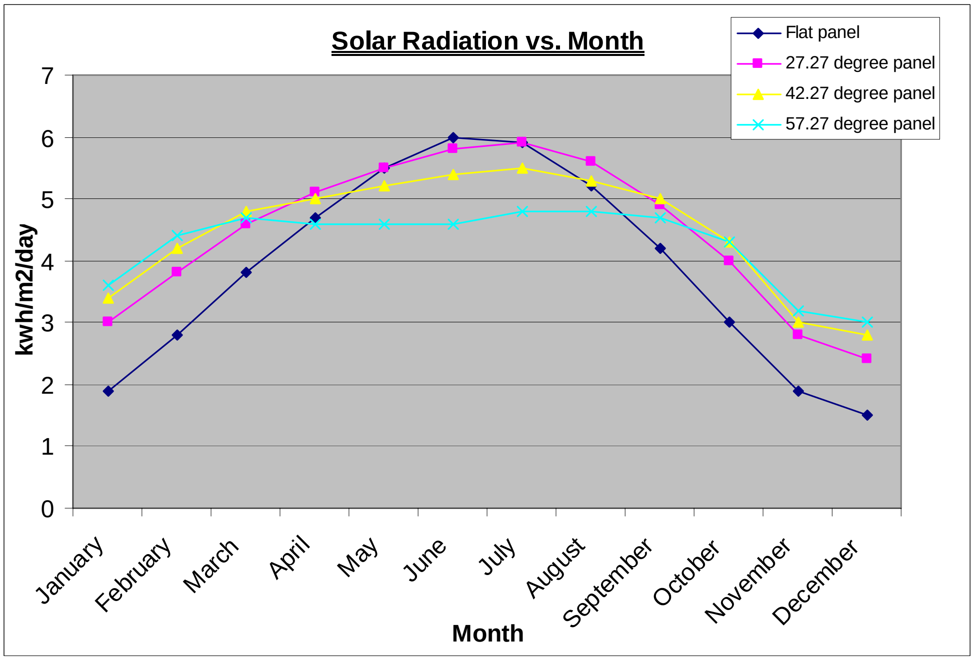

Figure 42: Solar Radiation in Worcester, MA *

Month	Flat (kWh/m2/day)	27.27 degrees orientation (kWh/m2/day)	42.27 degrees orientation (kWh/m2/day)	57.27 degree orientation (kWh/m2/day)
January	1.9	3	3.4	3.6
February	2.8	3.8	4.2	4.4
March	3.8	4.6	4.8	4.7
April	4.7	5.1	5	4.6
May	5.5	5.5	5.2	4.6
June	6	5.8	5.4	4.6
July	5.9	5.9	5.5	4.8
August	5.2	5.6	5.3	4.8
September	4.2	4.9	5	4.7
October	3	4	4.3	4.3
November	1.9	2.8	3	3.2
December	1.5	2.4	2.8	3

Table 3: Solar Radiation Data for Worcester, MA #

The amount of solar radiation present in Worcester throughout the year is dependent on the declination angle of the sun. In Figure 2 below, the sun's declination angles relative to the Equator and relative to Worcester are shown.[92] It is evident that the sun is never directly overhead in Worcester, therefore limiting the flat panels from being exposed to optimal sunlight. However, as shown in Figure 1 above, there is a time in June that the flat panel is the optimal orientation. At this time of the year, the sun's declination angle, relative to Worcester, is greater than -20^{o}. When this situation arises, all three angled panel orientations cause part of the radiation to be deflected. It is important to note that the ideal orientation of a solar panel is orthogonal, or perpendicular, to the primary direction of solar radiation.

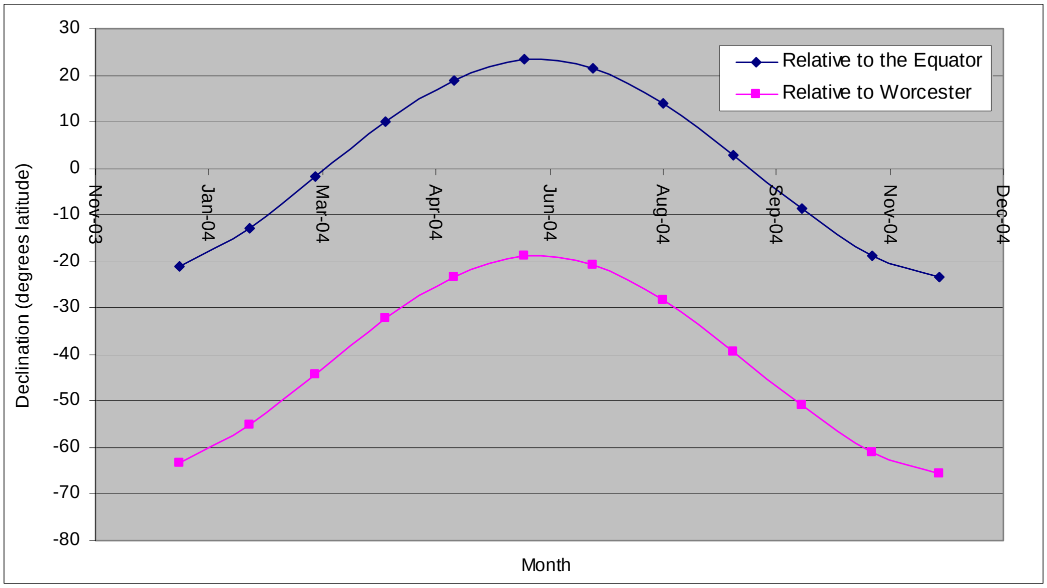

Figure 43: Declination Angle of Sun *

5.5.10.3 WPI Infrastructure and Energy Consumption

In order to produce electricity on campus, it was decided that the optimal location for solar panels would be on flat-roofed campus buildings. The requirement for solar panel placement on only flat roofs originated from technical and aesthetic limitations. First, buildings without south-facing or flat roofs would not be subject to sufficient solar radiation. Second, the orientation of solar panels on slanted roofs, such that they would noticeably change the aesthetics of the campus, was avoided. It is expected that the proposal of such an implementation would meet sharp criticism by both WPI faculty and students.

After obtaining the aforementioned data concerning solar radiation in Worcester, it was necessary to focus on campus buildings which could be sites for solar panel installation. AutoCAD drawings were obtained for each of the buildings on campus, and those buildings with partial or complete flat roofs were chosen as applicable for this study. In Table 2, the area of flat roof, in square meters, of each of the campus buildings is shown. The flat roof areas for each building do not account for any air conditioning or heating equipment or other devices that are located on the roofs, which would limit the available roof space which could be used. By summing the total flat roof area of each building, it was determined that the area of flat roofs at WPI totals 10,578 m^2.

Building	Flat Roof Area (m2)
Atwater Kent Laboratories	459.9
Fuller Laboratories	1058.7
Washburn Shops	914.5
Salisbury Laboratories	1010.5
Morgan Hall	1482.4
Goddard Hall	1379.9
Stoddard A,B, & C	915.9
Daniels Hall	1098.6
Stratton Hall	1048.5
Gordon Library	1209.5

Table 4: WPI flat roof space

Once the total roof area was measured, it was necessary to determine the consumption of electricity on campus. The consumption of electricity of each individual building could not be determined. However, the electricity consumption for the entire campus was attained, using available electricity bills from June 2003 and October 2004. Table 3 shows the service period, kWh consumption, number of days in each service period, and the calculated kWh/day consumption from each electricity bill. (The kWh/day consumption figures were calculated by dividing the kWh consumption by the days in that respective service period.)

Service Period	Days	kWh	kWh/day
June 25 - July 17	22	1199040	54501.81818
July 17 - Aug 15	29	1639680	56540.68966
Aug 15 - Sep 19	35	942960	26941.71429
Sep 19 - Oct 15	26	1397040	53732.30769
Oct 15 - Nov 14	30	1527600	50920
Nov 14 - Dec 17	33	1634160	49520
Dec 17 - Jan 19	33	1360800	41236.36364
Jan 19 - Feb 17	29	1388160	47867.58621
Feb 17 - Mar 22	34	1597440	46983.52941
Mar 22 - Apr 28	37	1857600	50205.40541
Apr 28 - May 17	19	956880	50362.10526
May 17 - Jun 16	30	1370880	45696
Jun 16 - Jul 16	30	1478400	49280
July 16 - Aug 24	39	1992240	51083.07692
Aug 24 - Sep 16	23	1410960	61346.08696
Sep 16 - Oct 18	32	1709760	53430

Table 5 : WPI kWh/day consumption (June 2003 – October 2004)

In Figure 3, the electricity consumption, in kilowatt-hours/day, is shown for the months corresponding to each service period. It is interesting to note that both the maximum and minimum kWh/day consumption over the past ~15 months occurred in August, the minimum occurring in 2003 and the maximum occurring in 2004. The explanation for this is unknown, though it can be postulated that mild climate conditions (low humidity and moderate temperature) during August of 2003 would have significantly decreased the need for extensive air conditioning.

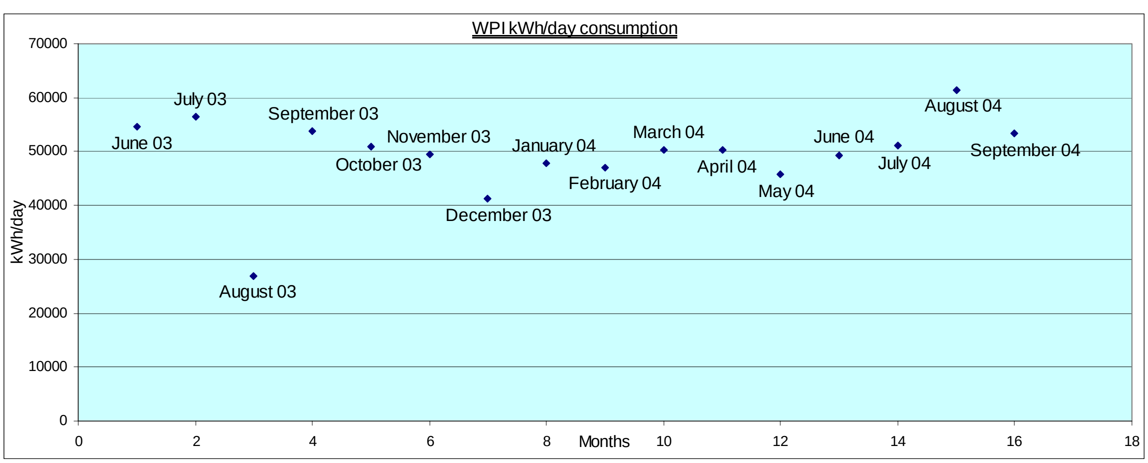

Figure 44: WPI kWh/day consumption

5.5.10.4 Potential Solar Power Systems

Now that both flat-roof space and electricity consumption of the WPI campus had been determined, it was necessary to explore the various options in terms of solar panels. Four leading solar panel manufacturers were considered, those being Kyocera, Sharp, BP Solar, and Sunwize.[93] In Table 4, the specifications of twelve different solar panels are shown, with wattage rating, dimensions, area (m^2), and cost per panel.

Manufacturer	Model Number	Watts	Dimensions (inches)	Area (m2)	Cost per panel
Kyocera	KC45	45	22.6" x 25.7"	0.37	$205
Kyocera	KC125	125	56" x 25.7"	0.92	$458
Kyocera	KC187G	187	56.2" x 39"	1.41	$710
Sharp	ND-070ELU	70	45.86" x 38.98"	1.14	$379
Sharp	ND-123UI	123	59.02" x 26.06"	0.98	$469
Sharp	NT- 185UI	185	62.01" x 32.52"	1.31	$729
BP Solar	SX20U	20	16.7"x16.5"	0.18	$165
BP Solar	BP485U	85	47.6" x 21.1"	1.01	$395
BP Solar	BP417OS	170	62.8" x 31.1"	1.26	$744
SunWize	OEM20	20	20.86" x 16.93"	0.23	$129
SunWize	SW85	85	56.93" x 22.8"	0.84	$349
SunWize	SW165-L	165	66.53" x 33.81"	1.45	$679

Table 6: Specifications of Various Solar Panels [#]

In order to determine the total electricity output of the various panels described above, it is essential to understand the wattage ratings of each solar panel. These ratings result from "flash testing" the solar panels in a laboratory setting. The flash is set at 1 kilowatt per square meter, which is equivalent to the amount of sunlight during a clear, bright day. The amount of watts produced by a flash of this light by the solar panel is therefore its wattage rating.

In order to determine which solar panel would be best in terms of energy production and cost, calculations were made concerning each panel's efficiency, cost per watt, and cost per m^2. The equations used for each of these calculations are shown below.

Panel efficiency = [(Watts)/(Area)]/(1000W/m^2) x 100% (1)

example: Kyocera (KC45) panel efficiency = [(45W)/(0.37m^2)]/(1000W/m^2) x 100% = **12.16%**

Cost per watt = (Cost per panel)/(Watts) (2)

example: Kyocera (KC45) cost per watt = ($205)/(45W) = **$4.56/Watt**

Cost per m^2 = (Cost per panel)/(Panel Area) (3)

example: Kyocera (KC45) cost per m2 = ($205)/0.37$m^2$) = **$554.05/m^2**

In Figures 4-6 below, the relationships between panel efficiency, cost per watt, and cost per m^2 for each panel are shown.

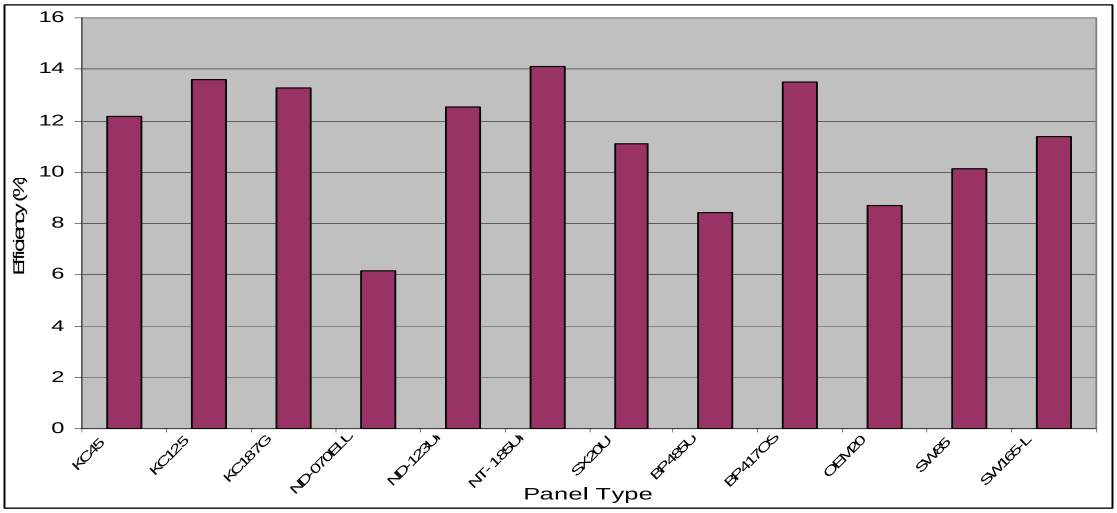

Figure 45: Solar panel efficiency *

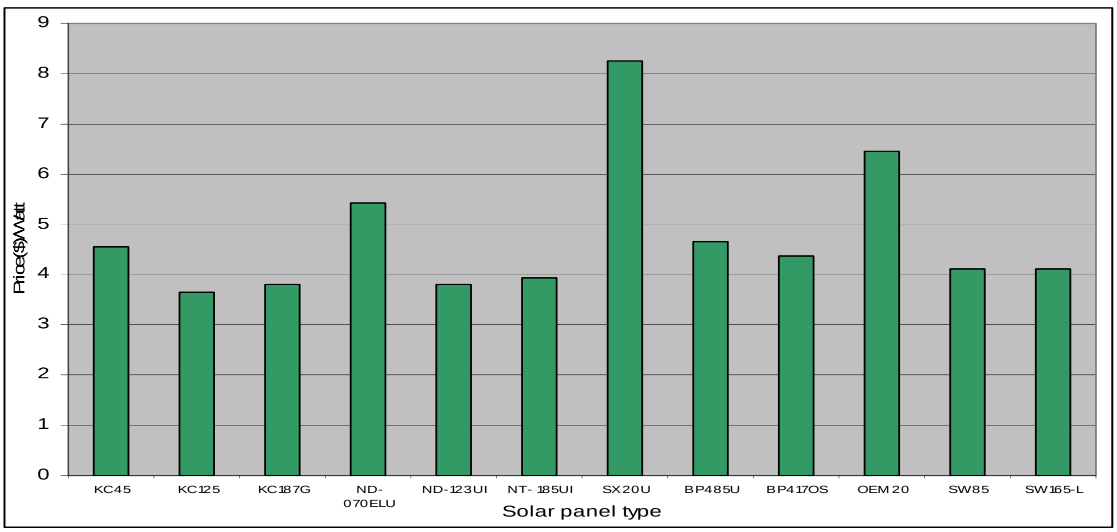

Figure 46: Solar panel cost per watt *

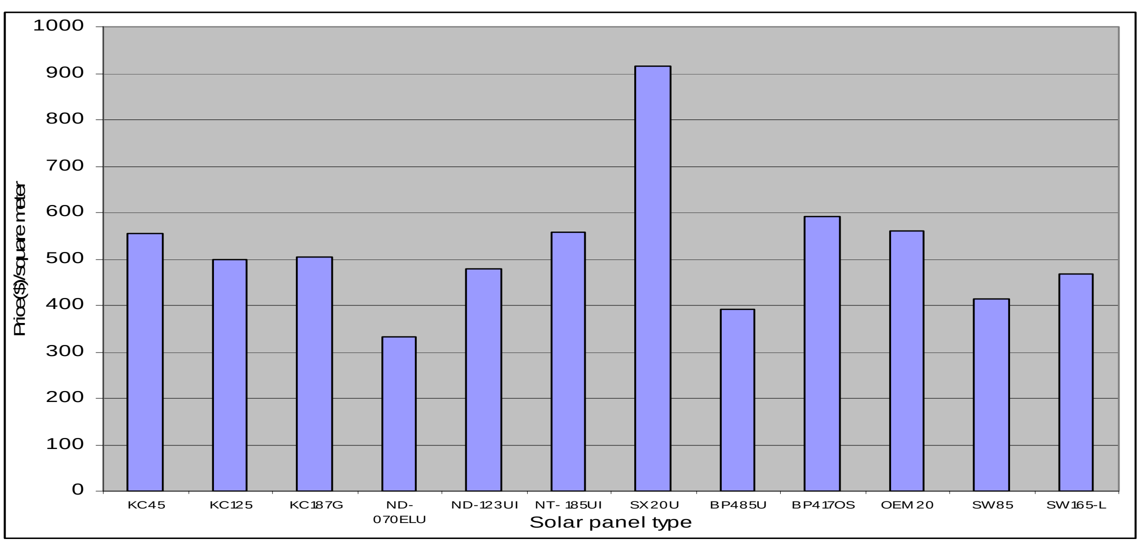

Figure 47: Solar panel cost per m^2 *

Based on the comparisons made in Figures 4-6, it is evident that there is not one particular panel which is superior in all three categories. The most efficient panel, in terms of converting solar energy to electricity, is the Sharp NT-185UI panel, with 14.12% efficiency. The most cost effective panel in terms of cost per watt is the Kyocera KC125 at $3.66/watt. The most cost effective panel in terms of cost per m^2 is the Sharp ND-070ELU at $332.46/$m^2$. For this report, the Sharp NT-185UI panel was chosen to due to its high efficiency and relative cost effectiveness. The cost characteristics of this panel are $556.49/m2 and $3.94/watt.

5.5.10.5 Solar Power Production

5.5.10.5.1 Horizontal Panel Placement:

The production of solar energy by a Sharp NT-185UI panel system is dependent on the orientation of the panels. The placement of solar panels horizontally on the roofs has two obvious benefits. First, the cost of materials would be lower than for angle panel placement because the panels can be fastened directly to the roof. Secondly, the panels do not cast a shadow onto north-ward positioned panels. For the horizontal placement of these panels, the following equations were used to determine solar energy production:

Number of panels = (Area$_{flat\ roof}$)/(Area$_{panel}$) (4)

calculation: (10578m^2)/(1.31m^2) = **8074 panels**

Total cost of panels = (Number of panels)*(Single Panel Cost) (5)

calculation: (8074)*($729) = **$5,886,535.88**

kWh/day produced = (6)

[(Number of panels)*(watts/panel)*(kWh/m^2/day (corresponding month)]/(1000Wh/kWh)

calculation (January): [(8074)*(185W)*(1.9 kWh/m^2/day)] /1000 = **2838 kWh/day**

* See Figure 7 for kWh/day production corresponding to each month

kWh produced per month = (kWh/day produced)*(days in month) (7)

calculation (January): (2838 kWh/day)*(31 days) = **87978.34 kWh/month**

***** See Figure 8 for kWh/month production for each month

Annual kWh production = ∑(kWh produced per month - for every month) (8)

% of WPI electricity consumption produced = (9)

(annual kWh production)/(WPI electricity consumption)

* WPI electricity consumption = ~18,192,292 kWh

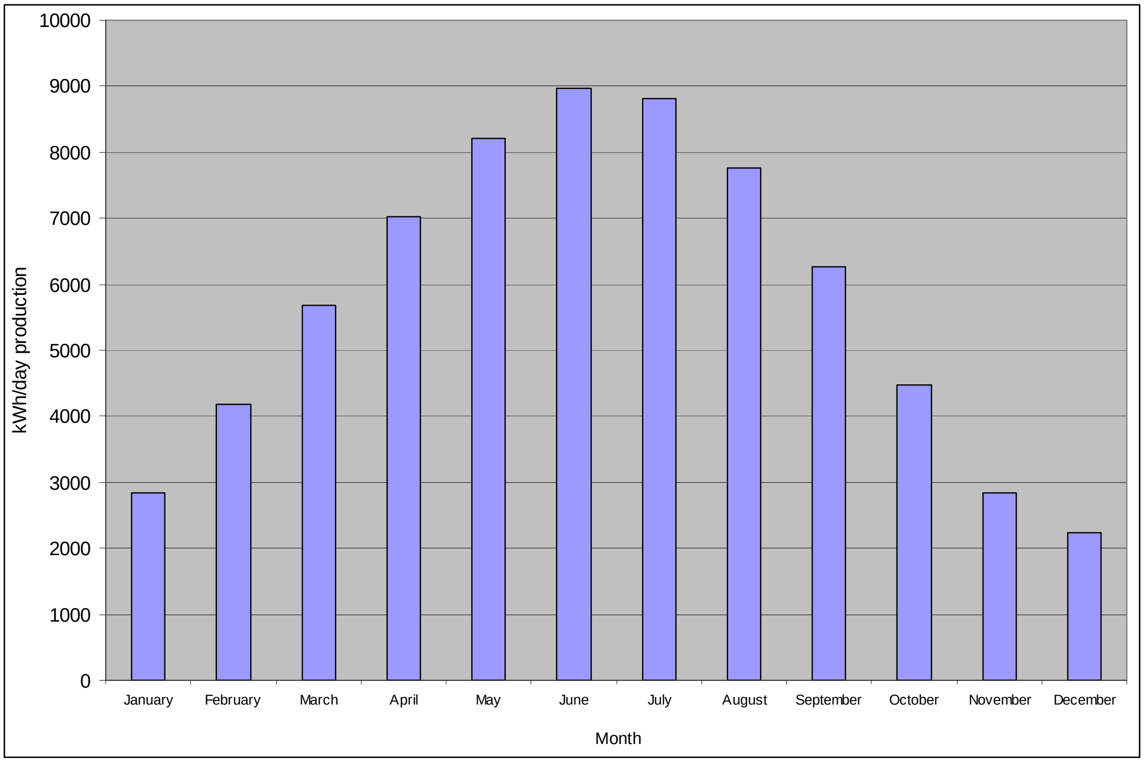

Figure 48: kWh/day production vs. month

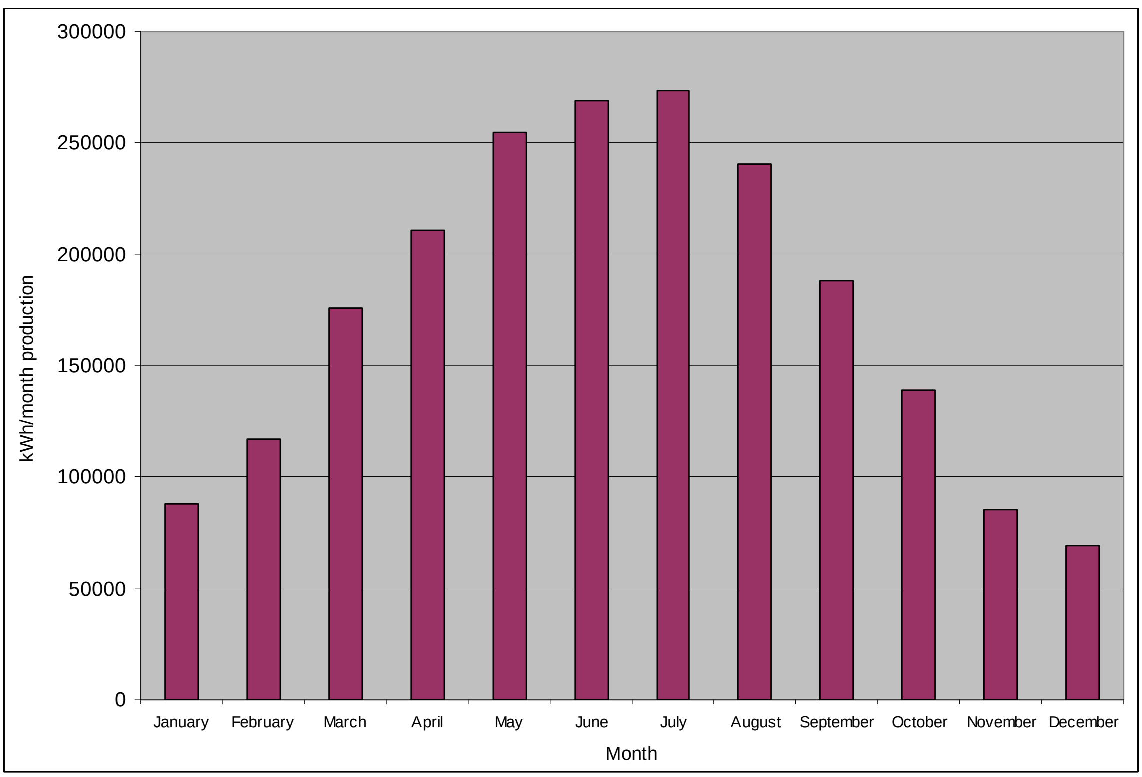

Figure 49: kWh/month production

Based on the calculations above, the number of panels that could be installed with this orientation is 8074. The total area of these panels is 10576 m^2, capable of producing 2,111,144 kWh annually. This system would replace 11.6% of WPI's annual electricity consumption, and save approximately $211,030 in annual electricity costs, based on current kWh prices.

5.5.10.5.2 Latitude minus 15° Angle Panel Placement

The placement of the solar panels on a south-facing angle allows for the panel to receive more direct sunlight, which increases kWh/m2/day exposure and solar energy production of the panel. However, when panels are placed on an angle, the cost of materials increases (panel angle brackets) and panels must be spaced such that shadows are accounted for.

The dimensions of the NT-185UI panel are 0.826m x 1.586m. For the purposes of this analysis, the panel was placed on its 1.586 meter side to allow for the smallest possible shadow length. As a note, it does not matter which side the panel is placed because the panel spacing versus lateral panel placement allows for equal numbers of panels to be placed on the roof. Essentially, if the panel is placed on its 0.826 meter side, the number of panels that can be placed side-by-side increases, but panel spacing also increases due to larger shadows.

The placement of the panel at a south-facing angle of 27.27° results in panel height of 0.378 meters, determined using Equation 10. The roof space occupied by the panel at this angle is 1.164 m^2, determined using Equation 11. Finally, the roof space covered by the maximum shadow cast by a panel at this angle is 1.319 m^2, determined using Equation 12. (The angle used in Equation 12 is equal to the sum of the sun's declination angle, relative to the Equator, and 42.27°, the latitude location of Worcester.)

$$Height_{panel} = (0.826m)*\sin(Angle_{panel}) \quad (10)$$

$$Height_{panel} = (0.826m)*\sin(27.27^o) = \mathbf{0.378\ meters}$$

$$Area_{panel} = (1.586m)*((0.826m)*\cos(Angle_{panel})) \quad (11)$$

$$Area_{panel} = (1.586m)*((0.826m)*\cos(27.27^o)) = \mathbf{1.164\ m^2}$$

$$Area_{shadow} = (1.586m)*[(Height_{panel})*\tan(Angle_{declination}+42.27^o)] \quad (12)$$

$$Area_{shadow} = (1.586m)*[(0.378m)*\tan(23.29^o+42.27^o)] = \mathbf{1.319m^2}$$

$$Area_{total} = Area_{shadow} + Area_{panel} \quad (13)$$

$$Area_{total} = 1.319m^2 + 1.164\ m^2 = \mathbf{2.48m^2}$$

$$\text{Number of panels} = (Area_{flat\ roof})/(Area_{panel}) \quad (4)$$

$$\text{Number of panels} = (10578m^2)/(2.48m^2) = \mathbf{4265\ panels}$$

The total area occupied by panel and shadow for each panel is simply the summation of the roof space occupied by the panel and shadow, which is 2.48m^2 in this case. With each panel accounting for 2.48m^2 of roof area, 4265 panels could be placed on the flat-roofed buildings. Each row of panels would be spaced by 0.832 meters, the length of a cast shadow when the sun is most oriented below the Equator. The total area of this number of panels would be 5,587 m^2, capable of producing approximately 1,282,481 kWh/year based on the solar irradiance associated with this panel angle. This amount of energy production would replace approximately 7.04% of WPI's annual electricity consumption, and save approximately $128,248 in annual electricity costs. Figure 9 shows the orientation of this panel.

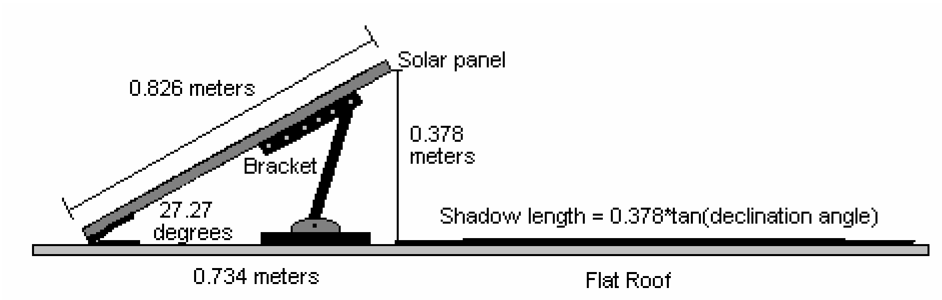

Figure 50: 27.27 degree panel orientation

Figure 10 shows the length of shadow relationship corresponding to the declination angle of the sun and the angle orientation of the panel. The 57.57^o angle panel has the largest cast shadow due to its panel height ($Height_{panel}$), as will be discussed shortly. Also, during the spring, summer, and fall months, the length of the cast shadow for each panel orientation is drastically lower than their respective shadow lengths in December and January.

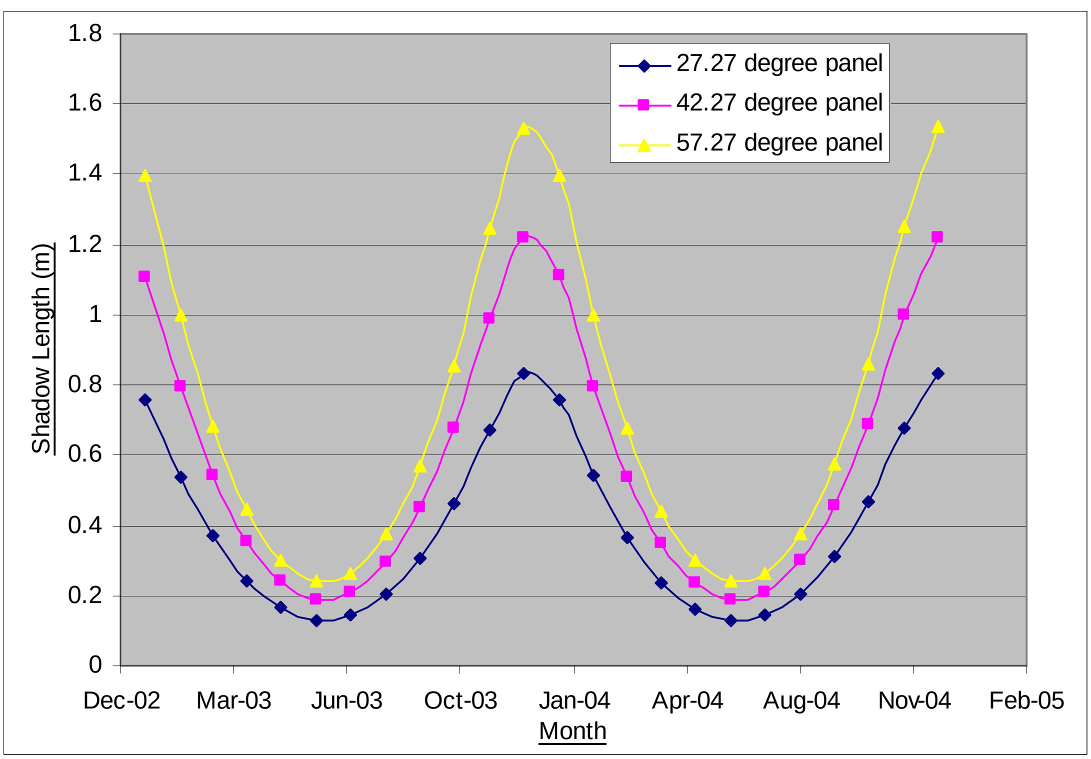

Figure 51: Shadow length per month

5.5.10.5.3 Latitude Angle Panel Placement (Figure 11)

The placement of the panel at a south-facing angle of 42.27° results in panel height of 0.555 meters, determined using Equation 10. The roof space occupied by the panel at this angle is 0.969 m^2, determined using Equation 11. Finally, the roof space covered by the shadow cast by a panel at this angle is 1.936 m^2, determined using Equation 12. The total area occupied by panel and shadow for each panel is therefore 2.91 m^2 in this case. With each panel accounting for 2.91 m^2 of roof area, 3666 panels could be placed on the flat-roofed buildings. Each row of panels would be spaced by 1.22 meters, the length of a cast shadow when the sun is most oriented below the Equator. The total area of this number of panels would be 4802 m^2, capable of producing approximately 1,112,196 kWh/year based on the solar irradiance associated with this panel angle. This amount of energy production would replace approximately 6.11% of WPI's annual electricity consumption, and save approximately $111,155 in annual electricity costs.

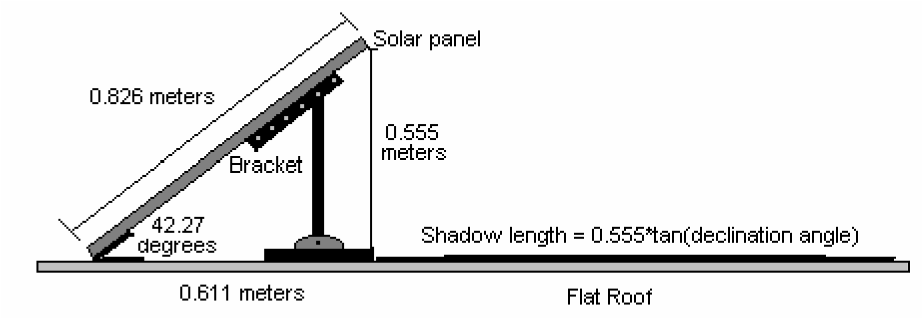

Figure 52: 42.27 degree panel orientation

5.5.10.5.4 Latitude plus 15° Angle Panel Placement (Figure 12)

The placement of the panel at a south-facing angle of 57.27° results in panel height of 0.698 meters, determined using Equation 10. The roof space occupied by the panel at this angle is 0.699 m^2, determined using Equation 11. Finally, the roof space covered by the shadow cast by a panel at this angle is 2.436 m^2, determined using Equation 12. The total area occupied by panel and shadow for each panel is therefore 3.13 m^2 in this case. With each panel accounting for 3.13 m^2 of roof area, 3397 panels could be placed on the flat-roofed buildings. Each row of panels would be spaced by 1.536 meters, the length of a cast shadow when the sun is most oriented below the Equator. The total area of this number of panels would be 4450 m^2, capable of producing approximately 980,374 kWh/year based on the solar irradiance associated with this panel angle. This amount of energy production would replace approximately 5.38% of WPI's annual electricity consumption, and save approximately $97,874 in annual electricity costs.

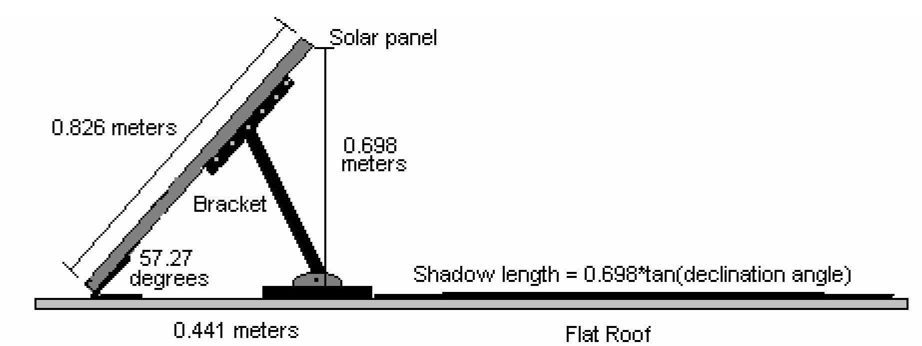

Figure 53: 57.27 degree panel orientation

5.5.10.6 Cost Analysis

The financial feasibility of replacing grid-dependent electrical systems with photovoltaics is the most prevalent deterrent to its implementation. The cost of energy per kWh from nonrenewable sources is far less than renewable energy kWh production. However, with full use of available federal and state incentives, it is possible to recover initial installation and material costs. The time for financial recovery depends primarily on kWh production incentives and increasing kWh costs from nonrenewable sources.

5.5.10.6.1 Incentives

5.5.10.6.1.1 Institutional Initiative

The first of two incentives that are available to Massachusetts non-profit institutions through the Massachusetts Technology Collaborative. Entitled the *Commercial, Industrial, & Institutional Incentive*, funding is distributed in the form of feasibility study grants, design grants, and construction grants. A total of $6 million was set aside in 2004 to be distributed over three years. For the year 2005, a total of $2,575,663 is available for renewable energy system construction. However, there is a limit on how much grant money any one renewable energy system can attain. Feasibility study grants will not exceed $40,000, design phase grants will not exceed $150,000 or 50% of design costs, and construction phase grants will not exceed $500,000 or 50% of construction costs. [94]

5.5.10.6.1.2 Mass Energy Incentive

The second Massachusetts institutional grant is the Massachusetts Energy Consumers Alliance REC (Renewable Energy Certificate) Incentive. This grant is available to any photovoltaic energy producer. For each kWh produced, Mass Energy will pay $0.06, or $60 per MWh. The grant is a three-year contract which can be renewed upon contract expiration. [95] This grant does not ensure that subsequent contracts would pay more than $0.06 per kWh as inflation reduces the value of money.

5.5.10.6.2 Net Present Value Analysis

The total cost of solar power implementation entails far more than just the panels themselves. Besides labor, costs include power production permits, inverters, panel brackets, and electrical connections to both the campus buildings and the grid. The cost of the panels accounts for between 45 – 55% of total installation costs. For the purposes of this analysis, it is assumed that the panel cost will only account for 45% of installation costs. Therefore, in determining the total initial cost for solar panel implementation, Equation 15 is used.

$$Cost_{initial} = Cost_{panels}*(55/45) - Incentive_{initial} \qquad (14)$$

To determine the period of time required to recover initial costs based on REC incentives and electricity cost savings, net present value analysis (NPV) was implemented, using Equation 15.

$$NPV = Cost_{initial} + (S + I)/(1 + r)^n \quad (15)$$

S = Electricity cost savings

I = REC incentives

r = inflation rate + interest rate

n = number of time periods (years)

Over the past ten years, the average annual inflation rate is 2.568%.[96] For the net present value analysis, an inflation rate of 2.6% was used. The interest rate used in this analysis was 2.35%, the current rate from ING Direct.[97] With these rates, r = 4.95%.

5.5.10.6.2.1 Flat Panel System

For the flat panel system, the cost for 8,075 panels would be $5,886,535, making the total system installation costs approximately $13,081,190. With the Commercial, Industrial, and Institutional grant accounting for a maximum of $690,000 (provided that feasibility, design, and construction grants are approved), the total initial cost ($Cost_{initial}$) would be $12,391,190. The annual production of this system would be approximately 2,111,144 kWh, which is 11.6% of WPI's kWh consumption over the past 12 months.

To find the electricity cost savings (S), 11.6% of WPI's annual kWh expenses were calculated to be approximately $211,114. These electricity cost savings are adjusted each year according to the 3.08% annual increase in kWh prices. The REC incentive of $0.06 per kWh would contribute $128,688 per year. (For this calculation, the assumption is made that the 6 cent incentive would not increase with inflation over the lifespan of the system, which is likely not the case.) The NPV equation is used to determine the financial feasibility for 25 years (the length of the warranty) and 40 years (the expected full lifetime of the system). With these costs, savings, and incentives, the net financial loss would be $6,509,795 after 25 years and $4,522,512 after 40 years.

5.5.10.6.2.2- 27.27^o angle panel system

For the 27.27^o angle panel system, the cost for 4,265 panels would be $3,109,185, making the total system installation costs approximately $6,909,299. The Commercial, Industrial, and Institutional grant is assumed to account for a maximum of $690,000, making the total initial cost to be $6,219,299. The annual production of this system would be approximately 1,282,491 kWh, which is 7.04% of WPI's kWh consumption over the past 12 months. To find the electricity cost savings (S), 7.04% of WPI's annual kWh expenses were calculated to be approximately $128,248. These electricity cost savings are adjusted each year according to the 3.08% annual increase in kWh prices. The REC incentive of $0.06 per kWh would contribute $76,948 per year. With these costs, savings, and incentives, the net financial loss would be $2,646,463 after 25 years and $1,308,009 after 40 years.

5.5.10.6.2.3- 42.27° angle panel system

For the 42.27° angle panel system, the cost for 3,666 panels would be $2,672,514, making the total system installation costs approximately $5,943,358. The Commercial, Industrial, and Institutional grant is assumed to account for a maximum of $690,000, making the total initial cost to be $5,253,358. The annual production of this system would be approximately 1,112,196 kWh, which is 6.11% of WPI's kWh consumption over the past 12 months. To find the electricity cost savings (S), 6.11% of WPI's annual kWh expenses were calculated to be approximately $111,219. These electricity cost savings are adjusted each year according to the 3.08% annual increase in kWh prices. The REC incentive of $0.06 per kWh would contribute $66,731 per year. With these costs, savings, and incentives, the net financial loss would be $2,053,288 after 25 years and $1,050,342 after 40 years.

5.5.10.6.2.4- 57.27° angle panel system

For the 57.27° angle panel system, the cost for 3,397 panels would be $2,476,413, making the total system installation costs approximately $5,503139. The Commercial, Industrial, and Institutional grant is assumed to account for a maximum of $690,000, making the total initial cost to be $4,813,139. The annual production of this system would be approximately 980,374 kWh, which is 5.38% of the WPI's kWh consumption over the past 12 months. To find the electricity cost savings (S), 5.38% of WPI's annual kWh expenses were calculated to be approximately $98,037. These electricity cost savings are adjusted each year according to the 3.08% annual increase in kWh prices. The REC incentive of $0.06 per kWh would contribute $58,822 per year. With these costs, savings, and incentives, the net financial loss would be $1,983,744 after 25 years and $1,108,274 after 40 years.

5.5.10.7 Cost Recovery Possibilities

Based on the cost analysis just discussed, it is clear that it is certainly not financially feasible to install a photovoltaic system based on the available incentives and the enormous initial cost for implementation. In order to make this proposition at all worthy of consideration, more grants would have to be attained and/or the expected savings and kWh production incentives would have to higher than those predicted.

Before examining possible methods by which solar power system implementation would become feasible, it is essential to determine how much government/ private funding would need to be provided such that the system would not produce a net financial loss after 25. (It is essential that the all costs are recovered by the end of the product warranty.) For the flat panel system, $6,509,795 in additional initial grant money would be required to break even after 25 years. Using the same analysis, $2,646,463 would be required for the 27.27° panel system, $2,053,288 for the 42.27° panel system, and $1,983,744 for the 57.27° panel system.

5.5.10.7.1 Federal/Private Grants

The most likely means of accessing the necessary funds explained above would be through federal or private grants. These sources of grants money might be directly or indirectly related to the solar panel system installation. For example, the federal government could possibility provide grants provided that WPI would dedicate a portion of the money to adding faculty or building a laboratory committed to photovoltaics/renewable energy research. Private funds may be provided by former WPI graduates or by a non-government affiliated alternative energy association.

Listed below are federal grants directly related solar power system implementation that were available during the past year (Feb 2004 – Feb 2005).

- $1 million grant - National Accreditation and Certification Program for Installation and Acceptance of Photovoltaic Systems, a program sponsored by the Department of Energy. [98]
- $75,000 grant - Environmental Quality Incentives Program, sponsored by the Department of Agriculture; for renewable energy installation projects. [99]
- $240,000 grant - Environmental Protection Agency; for development of sustainable energy programs. [100]
- Unspecified amount - Development and Maintenance of Testing Standards for Solar Energy Systems, sponsored by the Department of Energy; "…to advance the widespread application of solar energy technologies." [101]

Listed below are federal grants indirectly related solar power system implementation that were available during the past year (Feb 2004 – Feb 2005).

- Unspecified amount - Department of Defense; for research on nano-scale photovoltaics with the goal of achieving between 50 and 75% efficiency.[102]
- Unspecified amount - National Institute of Standards and Technology, in conjunction with the Department of Commerce; for research and development of alternative energy systems. [103]
- $850,000 grant - Information Dissemination, Education, and Public Outreach for the Solar Energy Technologies Program, sponsored by the Department of Energy; for teaching and marketing the benefits of solar energy. [104]

5.5.10.7.2 kWh Cost Projections

In the net present value analysis, it was assumed that the 3.08% yearly increase in kWh price would remain constant throughout the lifetime of the solar power system. However, based on the aforementioned predictions concerning nonrenewable energy resources, it is reasonable to expect that the annual kWh price increase will grow substantially as oil reserves run dry, causing substantial demand and price inflation for coal and natural gas. The annual kWh price inflation during the late 1970s, when the oil crisis was peaking, was approximately 12.3%, based on *National Grid* kWh price data. To introduce this type of kWh inflation into the net present value calculations, (12.3% - 3.08%) was divided by 40 years and the incremental 0.23% kWh increase was applied to each year of the NPV analysis.

The NPV analysis for this kWh increase prediction yielded the following results. For the flat panel system, there would be a net financial loss of $5,482,564 after 25 years and $414,514 after 40 years. For the 27.27° panel system, there would be a net financial loss of $2,022,439 after 25 years and a net financial gain of $1,549,039 after 40 years. For the 42.27° panel system, there would a net loss of $1,537,647 after 25 years and a net gain of $1,549,987 after 40 years. For the 57.27° panel system, there would be a net loss of $1,529,219 after 25 years and a net gain of $1,183,857 after 40 years.

It is important to note that this predicted % increase in kWh price cannot be stated with certainly because it is unknown when, or how quickly, the electricity market will react to drastically increasing oil prices as reserves are consumed. However, it is not outrageous to say that kWh prices could reach ~$2/kWh by the year 2050. The predicted kWh prices using the 3.08% yearly increase is ~ $0.34/kWh and it is a certainty that this will escalate according to escalating fossil fuel costs. In Figure # below, the kWh projected costs are shown for various predictions concerning % yearly kWh price increase in 2045, the end of the solar power system lifespan.

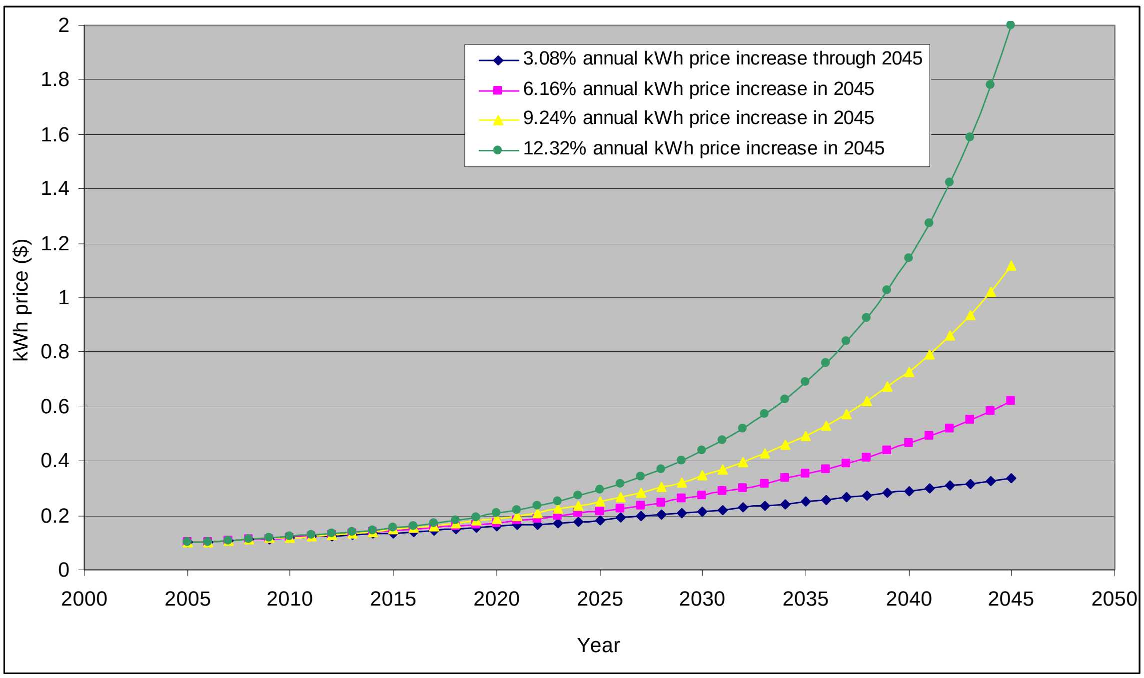

Figure 54: kWh cost projections

5.5.10.7.3 REC Incentives Inflation

As was noted in the NPV analysis, the Renewable Energy Certificate incentive was set at $0.06 per kWh throughout the lifetime of the system. Though it is uncertain as to how incentives will change according to increasing demand for renewable energy systems, it can be expected that the REC incentive will at least increase according to inflation. Applying a 2.6% inflation rate to the REC incentives, over the lifespan of the system, yields the following results.

For the flat panel system, there would be a net financial loss of $5,913,321 after 25 years, which is $596,473 less than the NPV without the adjusted REC incentives. For the 27.27^o panel system, there would be a net financial loss of $2,284,119 after 25 years, which is $362,344 less than the NPV without the adjusted REC incentives. For the 42.27^o panel system, there would a net loss of $1,753,876 after 25 years, which is $299,412 less than the NPV without the adjusted REC incentives. For the 57.27^o panel system, there would be a net loss of $1,719,819 after 25 years, which is $263,925 less than the NPV without the adjusted REC incentives.

5.5.10.7.4 Panel and Installation Savings

Another consideration for cost recovery is the potential savings associated with bulk purchasing of panels and WPI student-oriented installation. For the NPV analysis, the total cost of the panels was based on the premise that each panel would cost the listed price $729. For solar power systems requiring thousands of panels, as in this case, it can be expected that solar panel manufacturers/distributors would compete to have there panels installed in such a large scale proposition, thereby driving the price down. These price reductions cannot be predicted with any degree of certainty, but the assumption is made that the list price of $729/panel would be reduced by ~10% to $656/panel. The associated savings in total initial costs for each system would be as follows: $589,402 for the flat panel system, $311,345 for the 27.27^o panel system, $267,618 for the 42.27^o panel system, and $247,981 for the 57.27^o panel system.

In terms of installation costs, it is possible that WPI could allow students to install portions of system either as IQP or MQP projects, or hire work-study students to do the same. Based on the cost breakdown data from a solar energy installation in Chico, California, the cost of labor accounts for ~20% of total system implementation costs.[105] It cannot be expected that WPI could save 20% of its initial costs by using students as its source of labor. However, if WPI could save 10% using this method, the following initial cost savings would be achieved: $1,308,119 for the flat panel system, $690,930 for the 27.27^o panel system, $594,336 for the 42.27^o panel system, and $550,314 for the 57.27^o panel system.

5.5.10.7.5 Marketing Possibilities

If a solar panel system of this magnitude was in fact installed at WPI, it would be an achievement that would be well publicized throughout New England, New York, and possibly throughout the country. It would be the largest scale solar energy system in the Northeast, and its implementation would prove to potential renewable energy clients that, with the necessary funding, renewable energy systems are financially feasible, not to mention crucial in terms of environmental effects. This type of publicity would only benefit the school, in terms of attracting students and/or faculty that might have interests in renewable energy resources. WPI is currently in the midst of a marketing campaign which has allocated $2 million per year for a period of 4 years for the purpose of enhancing WPI image throughout the Northeast region and the country. If a portion of that money was diverted towards funding the solar energy system, it would serve a dual purpose of marketing the school and contributing to the benefits of renewable energy systems.

5.5.10.8 Social & Environmental Impact

As mentioned briefly in the marketing possibilities discussion, the impact of a large solar energy system implemented at WPI would have significant social and environmental impacts. The effect of this system on the surrounding community would be profound, proving that WPI is willing to take action towards finding a solution to severe environmental and natural resource depletion. Other universities and institutions, not to mention private businesses and households, might then follow suit and implement renewable energy systems. The high-tech image of the school itself would also be bolstered, for the implemented solar energy system would use the most modern photovoltaic technology.

The environmental impacts of this system would be astounding. Most grid-supplied electricity is generated using either coal or natural gas. Coal produces 1.6kg of carbon dioxide per kWh produced, while natural gas generates about 380g of carbon dioxide per kWh produced. [106] If the electricity supplied to WPI via the grid is coal-generated, the various solar panel systems would prevent the following carbon dioxide emissions: 3723 tons per year for the flat panel system, 2261 tons per year for the 27.27^o panel system, 1961 tons per year for the 42.27^o panel system, and 1729 tons per year for the 57.27^o panel system. If the electricity supplied to WPI via the grid is natural gas-generated, the various solar panel systems would prevent the following carbon dioxide emissions: 884 tons per year for the flat panel system, 537 tons per year for the 27.27^o panel system, 466 tons per year for the 42.27^o panel system, and 411 tons per year for the 57.27^o panel system.

5.5.10.9 California-based Solar Energy System

Upon examining the feasibility of a solar energy system in Worcester, a similar study was done based on southern California solar exposure and California incentives, in order to compare the practicality of solar energy systems in these two climates. The location in California that was chosen for this study was San Diego. To begin the study, it was necessary to determine the relationship between kWh consumption in California and kWh consumption in New England. This information was attained from the Energy Information Administration's Residential Energy Consumption Survey conducted in 1993, 1997, and 2001.[107] The survey had three categories which compared household consumption in the Northeast to California and its climate region, those being New England vs. West Pacific, climate zone 2 vs. climate zone 4, and New York vs. California. The survey data is shown below in Table 5.

NOTE: Climate zone refers to annual heating degree-days (HDD) versus annual cooling degree days (CDD) of a certain location. Massachusetts is located in Zone 2, with a CDD of less than 2,000 and an HDD of 5,500 to 7,000. California is located in Zone 4, with a CDD of less than 2,000 and an HDD of less than 4,000.[108]

	New England	West Pacific	Zone 2	Zone 4	New York	California
1993	7049 kWh	7775 kWh	8758 kWh	8954 kWh	5763 kWh	5924 kWh
1997	7062 kWh	8203 kWh	8727 kWh	9334 kWh	5879 kWh	6087 kWh
2001	7142 kWh	7622 kWh	9030 kWh	10118 kWh	5974 kWh	5948 kWh

Table 7: Residential Energy Consumption Survey Data [#]

As shown in Table 5 above, the annual household kWh consumption of the two regions varies substantially depending on which category is used for analysis. To determine the kWh consumption difference between California and Massachusetts, the percent difference between the Northeast and California regions, for each of the categories, was calculated. The resulting estimate for kWh consumption difference was that California households consumed 6.7% more kWh than Massachusetts households. Using this estimation, the predicted kWh consumption of WPI, if it was situated in San Diego, would be ~ 19,411,175kWh annually.

The solar radiation for San Diego is shown below, corresponding to the panel angle orientation.[109] When compared to the solar radiation measurements for Worcester, there are a few notable differences. First of all, as expected, the average solar radiation is significantly higher in San Diego than Worcester. For example, the minimal (flat panel) solar radiation in San Diego is 2.9 kWh/m^2/day while the minimum in Worcester is 1.5 kWh/m^2/day. For the San Diego solar radiation however, during the time of the year when the sun's declination angle with respect to the Equator is greatest, the efficiency of angled solar panels is much less than flat panels, especially for the 42.27^o and 57.27^o panel orientations. In fact, for the 57.27^o panel orientation, the amount of solar radiation exposure in June drops to the exposure level of the winter months.

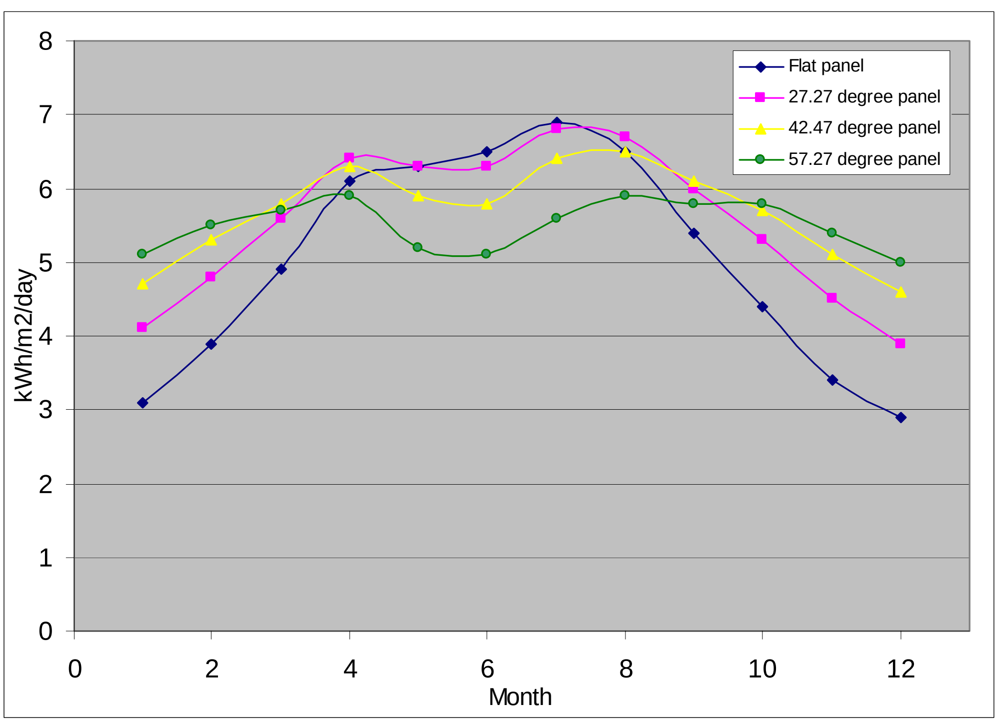

Figure 55: Solar Radiation (San Diego, CA) *

With solar radiation data and kWh consumption predictions for a WPI-sized institution in San Diego, the NPV analysis was applied to determine the financial feasibility of solar energy system implementation. The California incentive that is applicable to institutions, the Self-Generation Incentive Program, offers $3.50/watt during system installation.[110]

5.5.10.9.1 Flat Panel System

For the flat panel system, 8,075 panels would produce 2,743,053 kWh annually, which would be 14.1% of the total electricity consumption. The annual electricity cost savings would be $271,756, adjusted according to the expected yearly 3.08% increase in kWh prices. With the Self-Generation Incentive, the initial cost of the system would be $7,852,628. With these costs, savings, and incentives, the net financial loss would be $2,591,437 after 25 years (as opposed to $6,509,795 in Worcester) and $399,943 after 40 years (as opposed to $4,522,512. The environmental impact of this system would be an annual carbon dioxide emission of 4838 tons (for coal-generated electricity) or 1149 tons (for natural gas-generated electricity).

5.5.10.9.2- 27.27^o Angle Panel System

For the 27.27^o angle panel system, 5,755 panels could be installed due to smaller shadow lengths, producing 2,161,396 kWh annually and 11.1 % of total electricity consumption. The annual electricity cost savings would be $215,464, adjusted according to the expected yearly 3.08% increase in kWh prices. With the Self-Generation Incentive, the initial cost of the system would be $5,596,728. With these costs, savings, and incentives, there would be a net financial loss of $1,425,349 after 25 years (as opposed to $2,646,463 in Worcester) and a net gain of $312,194 (as opposed to a net loss of $1,308,009). The environmental impact of this system would be an annual carbon dioxide emission of 3812 tons (for coal-generated electricity) or 905 tons (for natural gas-generated electricity).

5.5.10.9.3- 42.27^o Angle Panel System

For the 42.27^o angle panel system, 4,911panels could be installed due to smaller shadow lengths, producing 1,885,210 kWh annually and 9.7 % of total electricity consumption. The annual electricity cost savings would be $188,288, adjusted according to the expected yearly 3.08% increase in kWh prices. With the Self-Generation Incentive, the initial cost of the system would be $4,775,940. With these costs, savings, and incentives, there would be a net financial loss of $1,130,688 after 25 years (as opposed to $2,053,288 in Worcester) and a net gain of $387,703 (as opposed to a net loss of $1,050,342). The environmental impact of this system would be an annual carbon dioxide emission of 3324 tons (for coal-generated electricity) or 789 tons (for natural gas-generated electricity).

5.5.10.9.4- 57.27^o Angle Panel System

For the 57.27^o angle panel system, 4,455 panels could be installed due to smaller shadow lengths, producing 1,654,366 kWh annually and 8.5 % of total electricity consumption. The annual electricity cost savings would be $165,383, adjusted according to the expected yearly 3.08% increase in kWh prices. With the Self-Generation Incentive, the initial cost of the system would be $4,332,480. With these costs, savings, and incentives, there would be a net financial loss of $1,130,688 after 25 years (as opposed to $1,983,744 in Worcester) and a net gain of $203,012 (as opposed to a net loss of $1,108,274). The environmental impact of this system would be an annual carbon dioxide emission of 2917 tons (for coal-generated electricity) or 693 tons (for natural gas-generated electricity).

5.5.10.10 Conclusion

After consideration of the analysis presented here, it is evident that a WPI solar energy system cannot be pronounced feasible conclusively. However, it is apparent that with proper planning and full use of available incentives/grants, this system could be implemented without financial loss and with profound social and environmental impact. The size of the system would be dependent on the amount of federal funding that would be available, such that the initial costs would be recovered within 25 years, the lifetime of the system warranty. Depending on the size of the system and/or the orientation of the panels, the necessary initial federal grants or marketing allotment would be between $5.5 million (the largest possible system) and $1.5 million (the maximum angle panel system). If substantial initial cost could be avoided via panel and installation savings, the required federal aid would drop significantly.

The social and environmental impact of such a system would affect primarily New England. It is a common belief that solar power systems are still not a viable means of replacing nonrenewable-generated power, especially in locations where solar radiation is not optimal. A system of this magnitude at WPI would be a significant step in proving this is no longer the case. Other universities would consider implementing their own systems, and other local private and public sectors would contemplate the possibility of solar energy. The environmental benefits of the system are unfathomable, preventing hundreds to thousands of tons of carbon dioxide emissions per year, depending on the system size and the type of resource (coal or natural gas) used for electricity production by grid-supplying power companies.

The comparison between solar energy systems in Massachusetts and California proved to be as expected. The implementation of a solar power system in a location where solar radiation is significantly higher allows for greater kWh production and carbon dioxide emissions savings. In terms of financial feasibility, California installation incentives are much higher than those in Massachusetts, allowing for quicker cost recovery. Based on this analysis, it is puzzling why solar energy systems are not more abundant in California and similar environments than they currently are.

Despite the encouraging results of this study, it is necessary to discuss the limitations of a solar energy system at WPI. The largest possible system that could be implemented, if all flat roof space was utilized, would only produce 11.6% of WPI's annual electricity consumption. The remaining 88.4% of

WPI’s electricity would continue to be obtained via nonrenewable resource power generation. Also, this system would do nothing to replace the non-electricity based consumption of fossil fuels, primarily oil for heating purposes. However, it can not be expected that renewable energy resources will immediately replace all nonrenewable energy generation methods. It will be a long drawn, slow out process of weaning society off of nonrenewables, at least until reserves begin to run out. At that point, society will be forced to find some method of harnessing the enormous potential of solar power. If WPI can be at the forefront of this movement, before the nonrenewable resources issue becomes a potential disastrous situation, it will benefit society as a whole.

6. Conclusion

The objective of this report was to examine nonrenewable and renewable energy resources and determine the most effective methods by which an impending fossil fuel crisis can be averted. The remaining reserves and consumption trends of natural resources were of utmost importance in predicting the timetable that exists before fossil fuel-dependent economies, such as the United States, will be forced to search for replacement energy sources. The implementation of renewable energy systems before this occurs will help the United States make a smooth transition from fossil fuels to renewable energy, and drastically aid in the movement towards stabilizing and improving the environment, which has suffered immensely from fossil fuel consumption.

Obtained from the U.S. Geological Survey and other resource-oriented organizations, the most recent estimations concerning oil, natural gas, and coal reserves were evaluated with respect to recent trends in production/consumption rates. Using linear regression analysis of the production/consumption data, it was determined what future rates will be, and how long the current reserves would last based on these rates. For oil, it was determined that reserves would be exhausted between 2038 and 2052. For natural gas, it was concluded that reserves would be exhausted between 2047 and 2049. For coal, it was determined that reserves would be exhausted between 2115 and 2121.

The analysis of renewable energy resources included hydropower, wind energy, and biomass conversion, but the primary focus was based on solar energy systems. In terms of a global solution to the impending fuel predicament, the possibility of launching geostationary solar power satellites was considered. Though in theory these satellites could provide more than enough power to supply the entire earth's needs, the cost of implementation would be astronomical. The size of these structures would require an installation process resembling the construction of the international space station, but at a larger level. Another limitation to this type of renewable energy source lies in the transmission of energy from the satellite to earth. Microwave transmission of energy would circumvent problems associated with cloud cover, but the possible associated environmental and health risks are not known. Also, due to the distance of transmission, the microwave receptor site would have to be enormous.

After analyzing the feasibility of solar energy implementation at WPI, it is evident that a system cannot be pronounced realistic. However, it is apparent that with proper planning and full use of available incentives/grants, this system could be implemented without financial loss and with profound social and environmental impact. The size of the system would be dependent on the amount of federal funding that would be available, such that the initial costs would be recovered within 25 years, the lifetime of the system warranty. Depending on the size of the system and/or the orientation of the panels, the necessary initial federal grants or marketing allotment would be between $5.5 million (the largest possible system) and $1.5 million (the maximum angle panel system). If substantial initial cost could be avoided via panel and installation savings, the required federal aid would drop significantly.

The social and environmental impact of such a system would affect primarily New England. It is a common belief that solar power systems are still not a viable means of replacing nonrenewable-generated power, especially in locations where solar radiation is not optimal. A system of this magnitude at WPI would be a significant step in proving this is no longer the case. Other universities would consider implementing their own systems, and other local private and public sectors would contemplate the possibility of solar energy. The environmental benefits of the system are unfathomable, preventing hundreds to thousands of tons of carbon dioxide emissions per year, depending on the system size and the type of resource (coal or natural gas) used for electricity production by grid-supplying power companies.

Despite the encouraging results of this study, it is necessary to discuss the limitations of a solar energy system at WPI. The largest possible system that could be implemented, if all flat roof space was utilized, would only produce 11.6% of WPI's annual electricity consumption. The remaining 88.4% of WPI's electricity would continue to be obtained via nonrenewable resource power generation. Also, this system would do nothing to replace the non-electricity based consumption of fossil fuels, primarily oil for heating purposes. However, it can not be expected that renewable energy resources will immediately replace all nonrenewable energy generation methods. It will be a long drawn, slow out process of weaning society off of nonrenewables, at least until reserves begin to run out. At that point, society will be forced to find some method of harnessing the enormous potential of solar power. If WPI can be at the forefront of this movement, before the nonrenewable resources issue becomes a potential disastrous situation, it will benefit society as a whole.

7. Appendix A:

Calculations used for nonrenewable resource predictions:

1. Linear Regression Equation:

$y = a + bx$

$a = [(\sum Y)(\sum X^2) - (\sum X)(\sum XY)]/[n(\sum X^2) - (\sum X)^2]$

$b = [n(\sum XY) - (\sum X)(\sum Y)]/[n(\sum X^2) - (\sum X)^2]$

Oil Example:

$\sum Y = 471{,}788.1$

$\sum X = 41{,}853$

$(\sum X)^2 = 1{,}751{,}673{,}609$

$\sum X^2 = 83{,}413{,}799$

$\sum XY = 940{,}493{,}949$

n = number of data points = 21

$a = [(471{,}788.1)(83{,}413{,}799) - (41{,}853)(940{,}493{,}949)]/[21(83{,}413{,}799) - 1{,}751{,}673{,}609] = 547{,}907$

$b = [21(940{,}493{,}949) - (41{,}853)(471{,}788.1)]/[21(83{,}413{,}799) - 1{,}751{,}673{,}609] = 286.19$

2. Standard error of the estimate for linear regression:

$s_{yx} = \sqrt{([n - 1 / n - 2](s_y^2 - b^2 * s_x^2))}$

Oil Example:

s_y = standard deviation of y-values (annual oil production numbers) = 1812.5

s_x = standard deviation of x-values (years) = 6.2048

b = slope of linear regression line = 290.88

n = number of data points = 21

$s_{yx} = \sqrt{([20/19](1812.5^2 - 290.88^2 * 6.2018^2))} = 173.22$

8. Appendix B:

Massachusetts Residential Incentives: (Taken directly from the Database of State Incentives for Renewable Energy)

"Renewable Energy State Income Tax Credit"[111]

Incentive Type: Personal Tax Credit
Eligible Technologies: Solar Water Heat, Solar Space Heat, Photovoltaics, Wind
Amount: 15%
Max. Limit: $1,000
Terms: May carryover unused credit for one or more of the next succeeding three taxable years.

"Mainstay Energy Rewards Program - Green Tag Purchase Program"[112]

Incentive Type: Production Incentive
Eligible Technologies: Solar Thermal Electric, Photovoltaics, Wind, Biomass, Geothermal Electric, Small Hydroelectric, Renewable Fuels
Amount: 1.7 - 6.4 cents/kWh; varies based on technology, payment plan, and contract length
Terms: Any size system, on-grid or off-grid, new renewable (1/1/98 or later)

"Mass Energy - Renewable Energy Certificate Incentive"[113]

Incentive Type: Production Incentive
Eligible Technologies: Photovoltaics
Amount: $0.06 per kWh
Terms: 3-year contract

"Local Property Tax Exemption"[114]

Incentive Type: Property Tax Exemption
Eligible Technologies: Solar Water Heat, Solar Space Heat, Solar Thermal Electric, Photovoltaics, Wind, Hydroelectric
Amount: All
Terms: 20 years maximum exemption; hydro facility owner must pay host community 5% of gross income for preceding year.

Appendix B (continued):

California Residential Incentives: (Taken directly from the Database of State Incentives for Renewable Energy)

"Tax Deduction for Interest on Loans for Energy Efficiency"[115]

Incentive Type: Personal Deduction
Eligible Technologies: Passive Solar Space Heat, Solar Water Heat, Solar Space Heat, Photovoltaics, Daylighting, Energy Efficiency
Amount: 100% of interest from loan
Terms: Loans from a publicly owned utility company

"California Property Tax Exemption for Solar Systems"[116]

Incentive Type: Property Tax Exemption
Eligible Technologies: Solar Water Heat, Solar Space Heat, Solar Thermal Electric, Solar Thermal Process Heat, Photovoltaics, Solar Mechanical Energy
Amount: 100% of project value

"Solar or Wind Energy System Credit – Personal" [117]

Incentive Type: Personal Tax Credit
Eligible Technologies: Photovoltaics, Wind
Amount: 7.5%, or $4.50 per watt of rated peak generating capacity, whichever is less
Terms: 7-year carry forward

"Self-Generation Incentive Program (SGIP)" [118]

Incentive Type: State Rebate Program
Eligible Technologies: Photovoltaics, Wind, Fuel Cells, Cogeneration, Other Distributed Generation Technologies
Amount: Between $1.00/W and $4.50/W depending on technology and fuel
Maximum Incentive: Incentive payment is capped at 1 MW

Appendix B (continued):

"Emerging Renewables (Rebate) Program" [119]

Incentive Type: State Rebate Program

Eligible Technologies: Solar Thermal Electric, Photovoltaics, Wind, Fuel Cells (Renewable Fuels)

Amount: $2.80/W (PV); $1.70/W for first 7.5 kW and $0.70/W thereafter (Wind); $3.20/W (Solar thermal electric and Fuel cells); PV performance-based incentive option is $0.50/kWh for 3 years.

Maximum Incentive: Maximum rebate varies by technology; $400,000 for performance-based incentive option

Note:

There are also multiple incentives which are granted by various cities and districts, including the following:

- Burbank Water & Power - Residential & Commercial Solar Support
- Anaheim Public Utilities - PV Buydown Program
- City of Palo Alto Utilities- PV Partners
- City of Riverside Public Utilities - Residential Photovoltaic Incentive Program
- City of Santa Monica - Green Building Incentives
- County of San Diego - Green Building Program
- Glendale Water & Power - Solar Solutions Program
- LADWP - Solar Incentive Program
- Redding Electric - Vantage Renewable Energy Rebate Program
- Roseville Electric - PV Buy Down Program
- San Diego - Residential Solar Electric Incentive for Homes Destroyed in Wildfires
- Santa Clara Water & Sewer - Solar Water Heating Program
- SMUD - PV Pioneers Residential Buy-down
- SMUD - Solar Water Heater Program Loan
- SMUD - Solar Water Heater Program Rebate

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