2008-03-11

Development of a Self Sustaining Building

Clinton B. McAdams
Worcester Polytechnic Institute

Devin S. Lavore
Worcester Polytechnic Institute

Scott McNee
Worcester Polytechnic Institute

Project Number: RWT-0802

Development of a Self Sustaining Building Through the Use of Alternative Sources of Energy

An Interactive Qualifying Project Report: Submitted to the Faculty of:

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the
Degree of Bachelor of Science
By:

Devin Lavore
dlavore@wpi.edu

Clinton McAdams
clinton@wpi.edu

Scott McNee
smcnee13@wpi.edu

Date: March 10, 2008

Professor Robert Thompson

Acknowledgements:

The group would like to extend a special thanks to Professor Thompson for all of his guidance, support, and patience. Without him this project would not have possible.

We would also like to acknowledge the following people for their generous contributions of time and effort:

- Doyle Conservation Center of Leominster, MA for the tour of their building and helping us get our project off the ground.
- Gilbane Construction Company with a special thanks to Melissa Hinton for her knowledge and assistance.
- Alfredo DiMauro for his contribution of crucial data for analysis within the project.
- Bob Katz for his expertise and wisdom on nuclear power and his generous donation of time
- Janet Richardson for her guidance and assistance in obtaining information regarding the East Campus Dormitory
- Kristin Tichenor for her guidance and assistance

Authorship

Formatting and Editing: Devin Lavore and Scott McNee

Review of Literature:

Nuclear Power- Scott McNee

Hydroelectric Power-Clinton McAdams

Geothermal Power-Clinton McAdams

Biomass Production-Scott McNee

Wind Power-Clinton McAdams

Solar Power-Devin Lavore

Hydrogen Power-Devin Lavore

Green Engineering:

LEED Certification-Devin Lavore, Clinton McAdams, Scott McNee

Zero Net Emission Homes-Devin Lavore

Overview of Non Applicable Technologies:

Nuclear Power-Scott McNee

Hydrogen Power-Devin Lavore

Overview of Applicable Technologies:

Solar PV Power-Devin Lavore

Biogas Production-Scott McNee

Table of Contents

Table of Figures

Table of Tables

Abstract

The purpose of this study was to evaluate the feasibility of converting the new East Campus Dormitory at Worcester Polytechnic Institute into a self sustaining green building. All possible alternative energy methods were researched, and the most appropriate technologies for on-site energy production were proposed. It has been estimated by WPI facilities that the building will need 2 MW of electricity per year, and will consume 42,600 Therms of natural gas annually. To meet this demand, a solar water heating system that consumes 95% less energy has been implemented in the proposed design. This, along with geothermal heat pumps allows for the complete elimination of natural gas from the building. The proposed roof mounted vertical axis wind turbines will produce 2.6 MW of power annually, which will satisfy the total electrical load of the building. By utilizing stricter green building practices, the energy demand of the structure can be even further reduced, which will allow for weather variations and other unforeseen circumstances which could affect energy production.

Introduction

Due to increasing environmental concerns and rising oil prices, the demand for alternative sources of energy has drastically increased over the past few years. The fossil fuels that we rely on today take hundreds of millions of years to create and, at the present rate of consumption, there will only be enough coal to last for another 100 years (Hoffert, Caldeira and Benford). In addition to the rapid depletion of oil reserves, harmful greenhouse gases are accumulating in the atmosphere, resulting in increasing global temperatures. Presently, there is enough carbon in fossil fuels to increase the planet's temperature by 10 °C (Hoffert, Caldeira and Benford). Utilizing alternative sources of energy not only has positive environmental applications, but also will decrease reliance on oil imported from other countries. Therefore, the need to create and develop sources of energy that do not involve carbon and fossil fuels has many advantages environmentally, economically, and politically.

The purpose of this study was to develop a system of alternative energies which will evaluate all of the East Campus Dormitory's energy needs; effectively making it a completely self-sufficient building which could be severed from the grid. To accomplish this goal, we researched all of the available alternative energies either in development or currently in use. This approach produced a multitude of on-site energy generation possibilities for a dormitory building. The system of energies which yielded the best combination of power and reliability was investigated further to determine an overall analysis of their possible effectiveness.

Review of Literature

This section reviews both current and future technologies in the alternative energy field that reduce carbon emissions and contribute to green energy production.

Nuclear Power

When it comes to alternative energy, nuclear energy is one of the frontrunners in the race to end this nation's dependency on foreign oil and reduce environmentally harmful emissions. Nuclear energy is potentially sustainable, the fuel source is secure, and the cost is about the equivalent of coal energy. The main problem with this type of energy is obviously the waste product and the disasters that have occurred at nuclear plants such as Windscale (October 10, 1957) and Chernobyl (April 26, 1986). Most people have negative connotations with the idea of nuclear energy; however, as this industry has grown it has improved safety immensely. Even now, reactor designs are being developed which will virtually eliminate the meltdown problems of the past and the older designs will soon be phased out of commission. Another concern rests with terrorist attacks, either on material in transit or at the plants themselves. All things considered, nuclear energy, as with all current alternative energies, will need extensive developing and research in order to be further incorporated into our economy.

Nuclear power plants are fueled by nuclear fission, a process which involves the splitting of the nucleus of an atom into parts, producing photons in the form of gamma rays, free neutrons and other subatomic particles as by-products. Fission of heavy elements, such as Uranium, is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments. In a critical fission reactor, like those most common in nuclear reactors, neutrons produced by fission of fuel atoms are used to cause even more fissions, to create a constant, usable energy source (Lipper and Stone). Fuel rods are then filled with enriched uranium oxide powder, sealed and placed together. This is where the nuclear reactions will take place. A typical fuel rod schematic is shown in Figure 1. The energy from fission generates heat, which is typically used to heat water, which turns to steam and is used to power turbines. Common types of nuclear reactors are pressurized water reactors, PWR, (Figure 2) and boiling water reactors, BWR, (Figure 3) (Alternative Energy Sources and Storage). The PWR includes many loops which reduces the amount of the reactor that is contaminated, whereas the BWR cuts down on the amount of loops and incorporates all of this into one stage of the reactor. There are many different designs in reactors, but all of those licensed in the U.S. are classified as either BWRs or PWRs. These types of reactors that are being designed today are similar, but not exactly alike, making them more expensive rather than a universal design that can be produced and repeated, much like an assembly line. With the amount of research being invested into nuclear possibilities, these designs will most likely be subject to revolutionizing changes, if they are not scrapped all together.

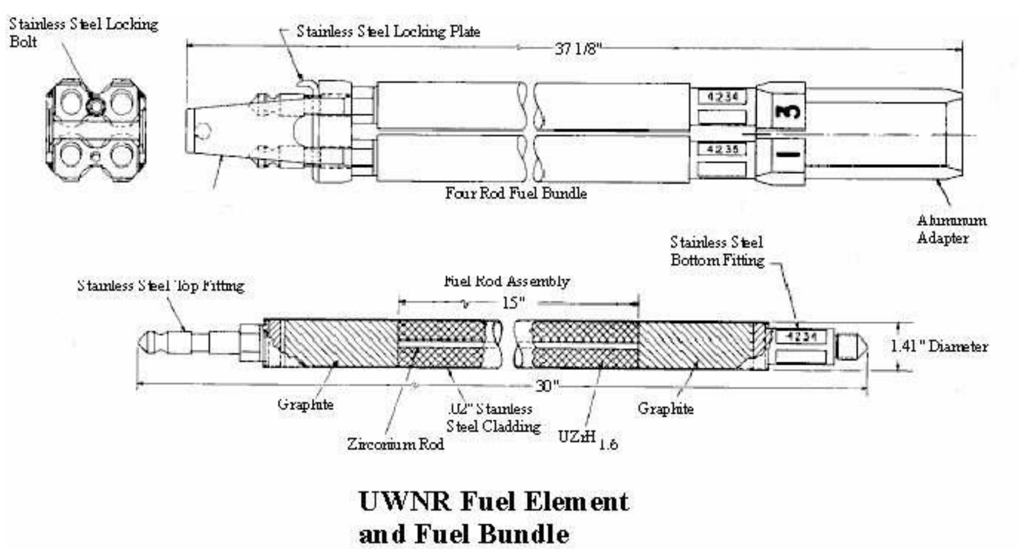


Figure 1: Fuel Bundle
(Alternative Energy Sources and Storage)

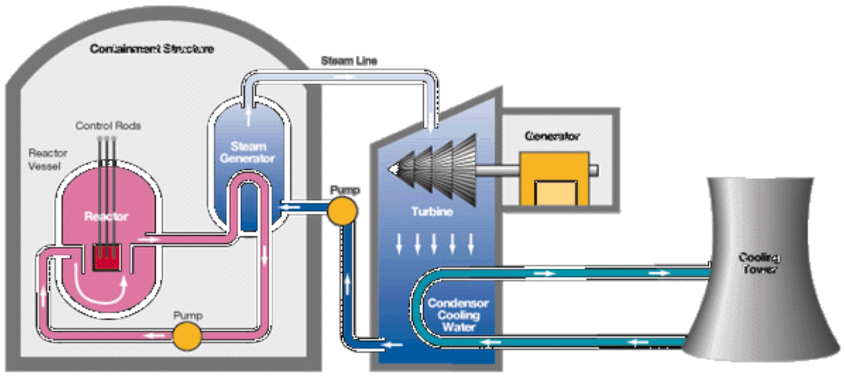


Figure 2: Pressurized Water Reactor
(Lipper and Stone)

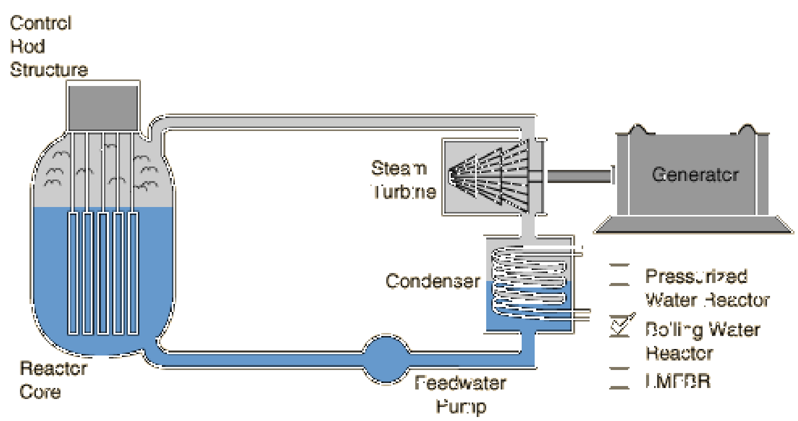


Figure 3: Boiling Water Reactor
(Nave)

Nuclear energy is already being used in the United States; as of October 31, 2005, there are 104 commercial nuclear generating units that are fully licensed by the U.S. Nuclear Regulatory Commission to operate in the United States. Of these 104 reactors, 69 are categorized a pressurized water reactors totaling 65,100 net megawatts (electric) and 35 units are boiling water reactors totaling 32,300 net megawatts (Nuclear Energy Overview). However, although the U.S. has the largest nuclear capacity of any nation, no new reactors have been built since May of 1996. Despite this, nuclear energy is not on a steep decline as many contractors have renewed their licenses and upgraded existing facilities. Annual net nuclear energy is shown in Figures 4 and 5.

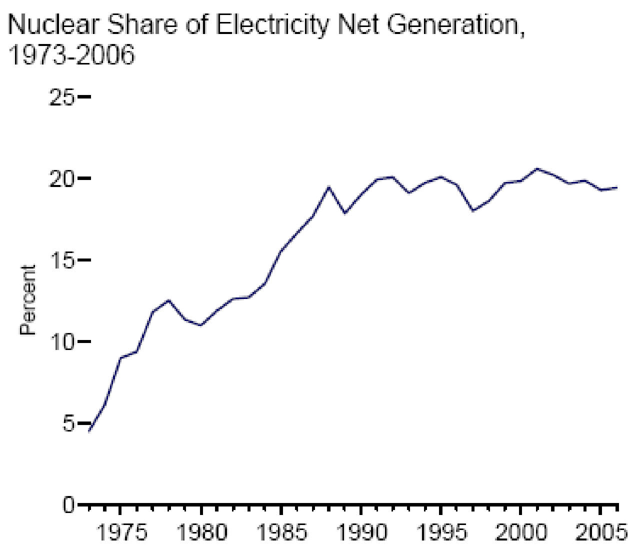


Figure 4: Nuclear Energy Overview
(Energy Information Administration)

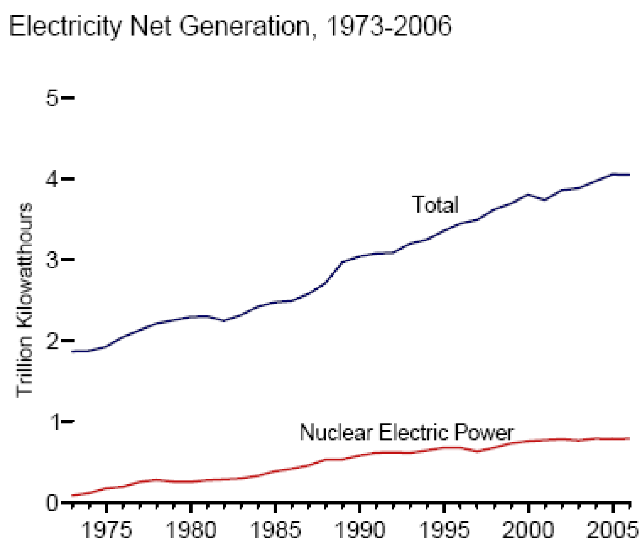


Figure 5: Nuclear Energy Overview 2
(Energy Information Administration)

A major problem limiting the increase or our nuclear plants is the safe and efficient storage of nuclear waste. This area has recently undergone major development in anticipation of the Yucca Mountain storage facility. A simulation of the repository is shown in Figure 6. The proposed area for this facility is 230 square miles of federal land, which the Department of Energy owns. The facility will address three major safety areas; preventing water from reaching the canisters, dissolving the canisters and waste, and carrying radioactive particles away from the repository. This will be accomplished by the multiple barrier strategy (Yucca Mountain Repository). This facility, if it becomes operational will be a much needed, standardized repository for nuclear waste. However, problems and delays continue to plague the project. Director Ward Sproat recently told lawmakers it was vital for Congress to allocate $494.5 million to carry out the latest schedule that calls for filing a license application to the Nuclear Regulatory Commission in June 2008 and a repository opening later in the next decade. This amount is still fifty million dollars less than what the project is already spending. However, Director Sproat is insistent that the deadlines for the licensing will be met, even if it requires that other parts of the project be delayed further. Senate house members have expressed impatience with the project's pace and encourage Director Sproat to increase the pace if at all possible (Blankinship). Along with storage, the issue of transportation comes into scrutiny. This is one area where the technology has not proved problematic. Nuclear waste has been shipped all over the country for 30 years for a total of over 1.7 million miles without any leakage or spills. This includes over 2,700 shipments of nuclear waste, and although this number will increase, the containment structures have evolved to ensure even more safety.

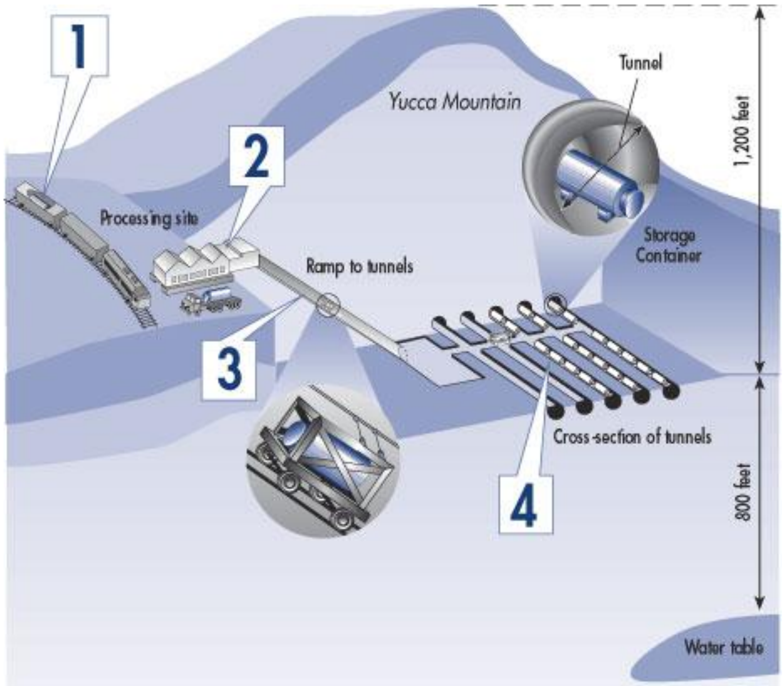


Figure 6: Yucca Mountain
(Conceptual Design of Yucca Mountain Disposal Plan)

These containment casks are subjected to rigorous tests including brutal crashes, 30 foot drops, engulfing fires at 800 degrees Celsius for 30 minutes, drops simulating puncture situations, and immersion in water for 8 hours. Although these casks can endure all sorts of punishment, the spent nuclear waste is in a solid, ceramic-like form that will not burn, leak or explode (Transporting Nuclear Waste). All of these shipments are strictly monitored and regulated by the Nuclear Regulatory Commission (NRC). The NRC regulates and licenses everything in the United States that deals with nuclear material. This includes everything from fuel cycle facilities that mill and enrich uranium and that fabricate it into fuel for use in nuclear reactors to the uranium mills located in the western part of the country. Although nuclear energy is an energy that requires extensive protection, regulation, and monitoring, the payoffs from nuclear reactors are well worth continued research and development.

The future of nuclear energy is extremely promising with the development of new reactor types and potential use for a nuclear-hydrogen economy. The newest reactor design is called a Pebble Bed Reactor, which integrates fuel spheres instead of the traditional fuel rods as well as a helium heat transfer system. The Pebble Bed Modular Reactor is a design being developed by Pebble Bed Modular Reactor Ltd. of South Africa which hopes to mass produce their design in the future. The PBMR team includes a second South African company; Potchefstroom based M-Tech Industrial (Pty) Ltd. The other members of the group are Shaw Stone & Webster of Boston; Technology Insights of San Diego; Air Products and Chemicals of Allentown, Pennsylvania; Nuclear Fuel Services of Erwin, Tennessee; and, Kadak Associates of Providence, Rhode Island. This design consists of eight reactor modules, 165 MW per module, with capacity to store 10 years of spent fuel in the plant, with possible storage outside of the facility (What is PBMR?). The PBMR core is based on the German high-temperature gas-cooled reactor technology and uses spherical graphite elements containing ceramic-coated fuel particles (Backrounder on New Nuclear Plant Designs). Toshiba is also developing a smaller, modular, battery-like reactor dubbed the “4S,” which stands for “Super-Safe, Small and Simple.” However, the word small is used in reference to normal nuclear reactors. It produces 10 to 50 mega-watts, and is about the size of a water tower and is sodium cooled. However, current regulations require roughly 34 armed guards for security purposes, the regulations have not been adapted for the newer, smaller designs, therefore every reactor is treated as a large scale major power plant (Backrounder on New Nuclear Plant Designs). Toshiba has plans to install a 4S reactor in Galena, Alaska to power a remote village by 2010, although no formal licenses have been discussed with NRC (Adams). Designing and developing these types of nuclear reactors will be crucial in reducing greenhouse gas emissions and powering our country with nuclear energy in the future.

Another widely discussed use for nuclear energy lies with combining a hydrogen economy with the nuclear industry. Nuclear power plants could provide plenty of energy to make the hydrogen that is proposed to power vehicles in the future. This could potentially reduce the need for smaller, compact nuclear power plant designs at the same time. However, all of these propositions are in theory as there is little talk of such a combination being designed or produced anytime soon. If such a concept were implemented, central nuclear plants could produce hydrogen for vehicles as well as supply large amounts of commercial electricity (Zink). Nuclear energy is a powerful and sustainable source and can be harnessed safely and in all likelihood will be a major part of this country's energy economy in the future.

Hydroelectric Power

Hydroelectric power is also another powerful, renewable source of energy. There are two methods of hydroelectric generation: impoundment and diversion. Impoundment is the most common form of hydroelectric generation. This method uses a dam to block a river and creates a reservoir. Water from the reservoir is released down a channel and flows past turbines to generate electricity. Water can be released at a constant rate or timed to be released at times of high power demand thus providing peak load power. The method of diversion does not block the river instead it only uses a portion to drive turbines. Diversion systems can only provide a constant power rate to meet the base load requirements (Beck, Renewable Energy Fact Sheet).

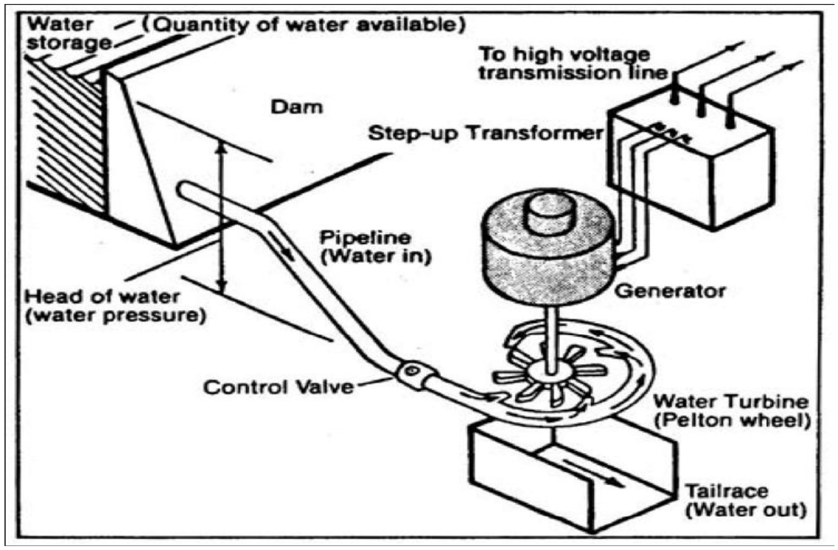


Figure 7: Diagram of Hydroelectric Scheme
(Australian Institute of Energy)

Hydroelectric power generation is a renewable energy source. Also, because no fossil fuel is needed to generate electricity there are no CO_2 emissions (Environmental and Energy Study Institute). "According to the US Office of Energy Efficiency and Renewable Energy, if fossil fuels had been used to generate the energy that hydropower plants produced in 1999, 77 million additional metric tons of carbon would have been emitted into the atmosphere, equivalent to the amount of carbon emitted by half the passenger cars driven in the United States in 1999 (Beck, Renewable Energy Fact Sheet)."

The largest issues with hydroelectric plants are the large capital costs. Another large problem is that dams cause the destruction of land and the displacement of people and animals. An example of this is the Three Gorges Dam in China. When completed, this dam will generate 84.7 billion kWh of energy annually, a number equivalent to 15 typical nuclear power plants. The reservoir created by this dam is expected to cause the relocation of 1.2 million people and cover 31,000 hectares of farm land, and 1599 industrial and mining enterprises (Xinhuanet).

Two well known hydroelectric power plants are the Hoover Dam and the largest hydroelectric power plant in the United States, Grand Coulee Dam. The Hoover Dam produces 4.8 billion kWh a year from seventeen main turbines. The energy produced at the Hoover Dam is used by 1.3 million people in Nevada, Arizona, and California (USBR GOV). The Grand Coulee Dam in Washington produces 21 million MWh a year from thirty-three main turbines. The energy produced at Grand Coulee is distributed to eleven states (USBR GOV).

Geothermal Energy

Geothermal is an incredibly powerful source of energy and it has been used by people for hundreds of years but has only been used for electrical generation since 1904 (Fact Sheet 9: Geothermal). Geothermal energy accounted for 7% of United States electricity generated from renewable sources. The United States is the world's largest generator of geothermal energy producing about 2800 MW annually. Geothermal energy's cost is about three cents to eight cents per kWh produced (Beck, Renewable Energy Fact Sheet: Geothermal).

Geothermal energy comes from heat in the earth's core. This heat creates hot water and steam which can be tapped into and used for the generation of electricity. This hydrothermal energy is normally found 100 meters to 4.5 kilometers under the ground. The temperature of the water and steam can be anywhere from 100°C to over 350°C (Fact Sheet 9: Geothermal). Energy is produced by pumping the steam from underground into a turbine. After that the steam is cooled and condensed then pumped into a reservoir or back into the ground (Dickson and Fanelli).

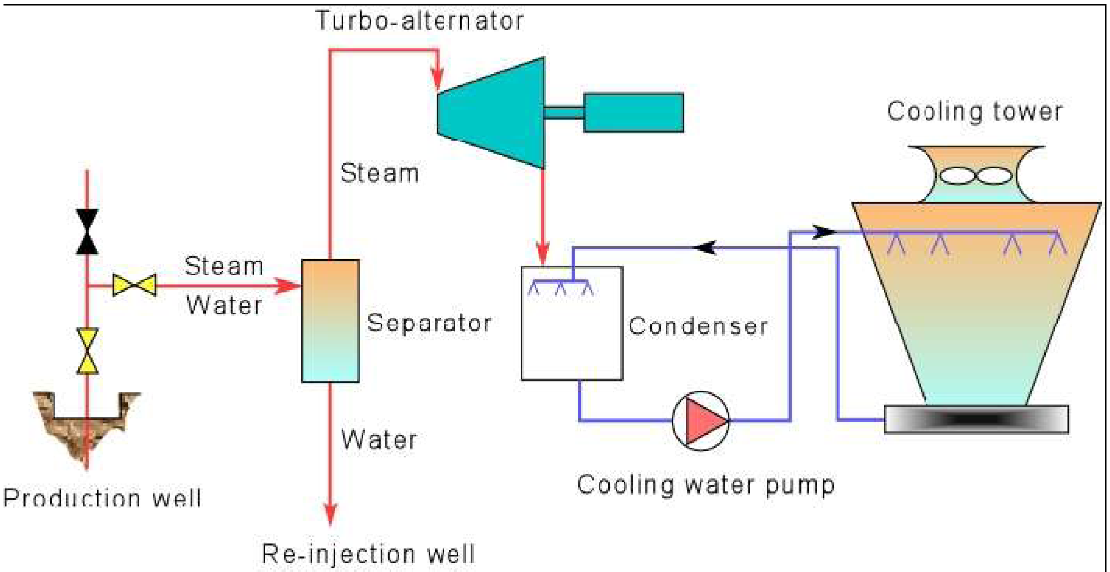


Figure 8: Condensing geothermal power-plant
(Dickson and Fanelli)

Another use of geothermal energy is in heating and cooling applications. In this instance heat pumps are used to take advantage of the earth's constant temperature of 50°F to 60°F at about ten feet deep. During the winter months, heat from the warmer ground is pumped into the building while during the summer the hot air in the building is pumped underground and through a heat exchanger. This heat removed during the summer can also be used to heat water (Beck, Renewable Energy Fact Sheet: Geothermal).

The major advantages about geothermal energy are that it is available 24 hours a day. Also, geothermal steam emits 35 times less CO_2 then the average coal power plant per kilowatt of energy produced. In one year geothermal power plants prevent 4.1 million tons of CO_2 emissions (Beck, Renewable Energy Fact Sheet: Geothermal). Figure 9 shows that the majority of these areas are west of the Rocky Mountains and lie on seismically active areas. Although geothermal energy has many advantages, there is simply not enough concentrated land area to use this energy throughout the nation.

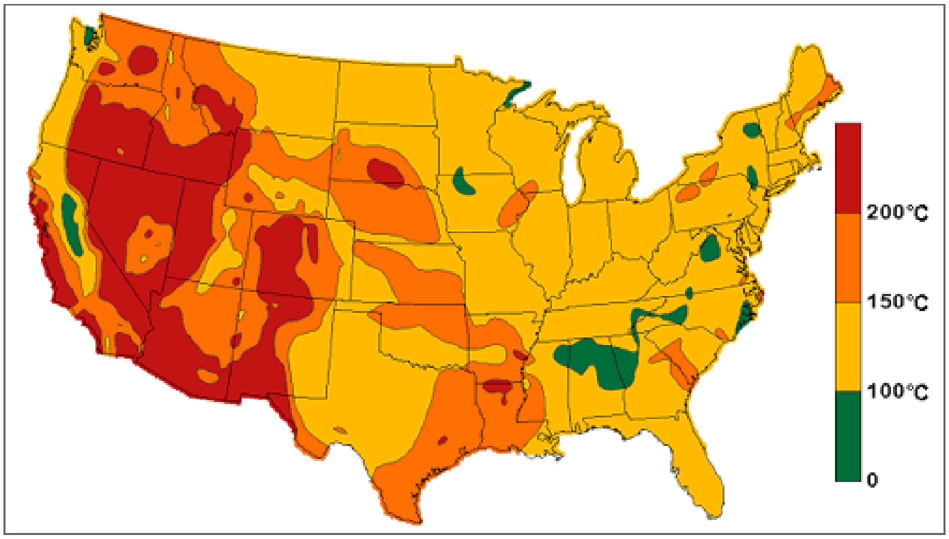


Figure 9: Earth's Temperature at 6 kilometers
(US DOE 2006)

Biomass Fuel Technology

There are many different sources for biomass; this includes food crops, grassy and woody plants, the organic component of municipal and industrial wastes, fumes from landfills, and other ways to derive energy from plant materials. Biomass can be made into fuels, products or into power production. Biomass reduces greenhouse emissions and it will reduce our country's dependence on foreign oil as it is a renewable source of energy. Bio-energy ranks second in renewable U.S. primary energy production but provides only three percent of the primary energy production in the United States (Energy Sources- Bioenergy). The main contributors of biomass are paper and lumber mill scrap and municipal waste. Biofuels such as corn and soybeans are surplus crops which can be used to derive ethanol and biodiesel, respectively. Biomass and biofuels can be made from a large variety of sources, which leads to their feasibility as a part of our fuel economy.

Biodiesel is a common form of alternative energy that is not petroleum based, but is blended with petroleum diesel to reduce emissions. This blend can range anywhere from 5 to 85 percent, although any blend higher than 20 percent will require modifications to the engine. This biodiesel is made by combining alcohol with vegetable oil, animal fat, or recycled cooking grease, where the alcohol used is typically methanol (Learning About Renewable Energies: Biofuels). The chemical process in this reaction is called transesterification, where the by-product glycerin is separated from the fat or vegetable oil. After the process is completed it leaves two remnants; methyl esters (biodiesel) and glycerin. Glycerin is usually sold to companies to be used in soaps and other products, therefore this process has no waste products, obviously what leads to its popularity. This biodiesel must meet strict regulations in order for it to pass emissions tests, which is what makes it different from raw vegetable oil. A problem with biodiesel is its relatively short shelf life of 18-24 months without additives. Biodiesel blends of as low as 2 percent can reduce the cost of diesel fuel by 2 to 3 cents per gallon (Biodiesel Basics). Most vehicles utilizing biodiesel fuel are United States fleets, over 25,000 vehicles in public transportation, government use and others. There are currently 165 biodiesel plants in the United States and these plants support the agricultural and forest product industries. Farmers have also expressed interest in biodiesel fuel, as they have collectively invested 25 million dollars in the product (Biodiesel on the Farm). An advantage of biofuels is their increased lubrication, which decreases engine wear and is also easier on the environment, a major selling point for the agricultural industry. Biofuels have also caught the attention of the military. In fact Honeywell's UOP in Des Plaines, IL was recently given $6.7 million from the U.S. Defense Advanced Research Projects Agency to create a bio-based jet fuel. This will be the ultimate test for biofuels as the military will require extremely high performance (Bryner). Although biodiesel does not completely solve our dependence on petroleum as there are not enough resources to fully power our nation, it can potentially reduce green house emissions and other pollutants until a solution is found to curb our nation's appetite for petroleum.

Another fuel additive or alternative energy is ethanol, which has already been introduced into the U.S. fuel economy. This fuel can be used as an octane boosting additive in gasoline while also reducing pollution (of the vehicle's exhaust). In order to make ethanol, a plant is needed for the steps to transform cellulosic biomass, such as agricultural forestry residues, industrial waste, material in municipal solid waste, trees, and grasses into fuel grade ethanol. The process involves fixing carbon dioxide into organic carbon and converting this biomass into a useable fermentation feed, usually a type of sugar. Then the sugar is fermented, producing ethanol in a dilute, liquid solution. This step requires using yeast, bacteria and other microorganisms. This solution is made into ethanol and other byproducts by further processing the solution. As of now 81 ethanol plants in 20 states have the capacity to produce nearly 4.4 billion gallons annually. There are plans for 16 more plants to add another 750 million gallons of capacity to the existing plants. New methods known as advanced bioethanol technology is capable of breaking down the complex sugar chains of cellulose and hemicellulose of corn stalks, sawdust, or waste paper into fuel ethanol (Energy Efficiency and Renewable Energy: Ethanol). Once again, the ethanol is currently seeing most of its use as a fuel additive, which is not completely solving our dependence on petroleum, but is a step in the right direction by reusing and recycling waste products and attempting to reduce carbon emissions from non renewable sources.

There are many different sizes and types of biorefineries, but most follow a universal concept. One of these concepts is by utilizing anaerobic digestion, a process in which methane is produced from the decomposing organic waste. This occurs naturally in landfills, which can also be tapped by drilling to release the methane from decaying organic matter. Of course, this methane must be cleaned before it can be used for burning, but it is naturally occurring and renewable. Another method to derive methane from biomass is in digesters, which seal the decomposing matter from oxygen, which will produce gas for power and turn otherwise unusable waste into compost. These digesters, which use processes such as anaerobic digestion or gasification, a schematic of gasification is shown in Figure 10, can be adapted into smaller, modular systems. Such designs are soon to make a breakthrough and these 5 kW to 5 MW systems are expected to lend themselves to high volume manufacturing techniques to bring them on a competitive level with large stand-alone plants (Smaller Modular Gasification).

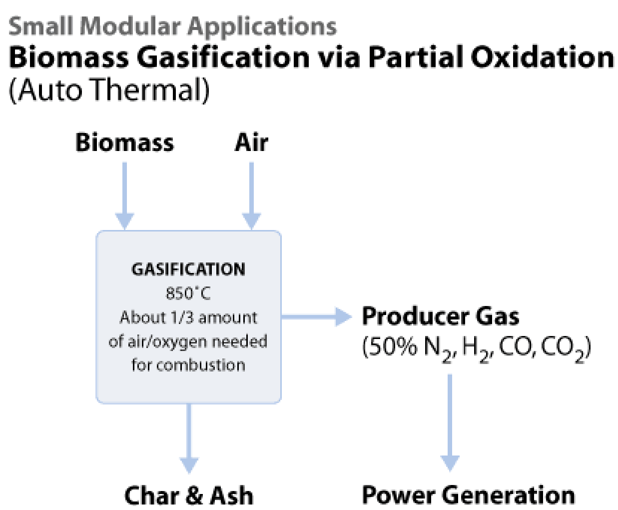


Figure 10: Gasification
(Smaller Modular Gasification)

Biomass digesters, such as the one shown in Figure 11, utilize anaerobic digestion, which is a process that incurs three phases. For each phase, there is a certain group of microorganisms, the first stage converts organic material to a form that a second group of organisms utilizes to form organic acids. Then methane producing organisms complete the process and gas, about 50-80 percent methane, is produced along with carbon dioxide (20–50%), and trace levels of other gases such as hydrogen, carbon monoxide, nitrogen, oxygen, and hydrogen sulfide. For such gas, for every cubic foot about 10 BTUs are produced for every percent of methane composition (Darling).

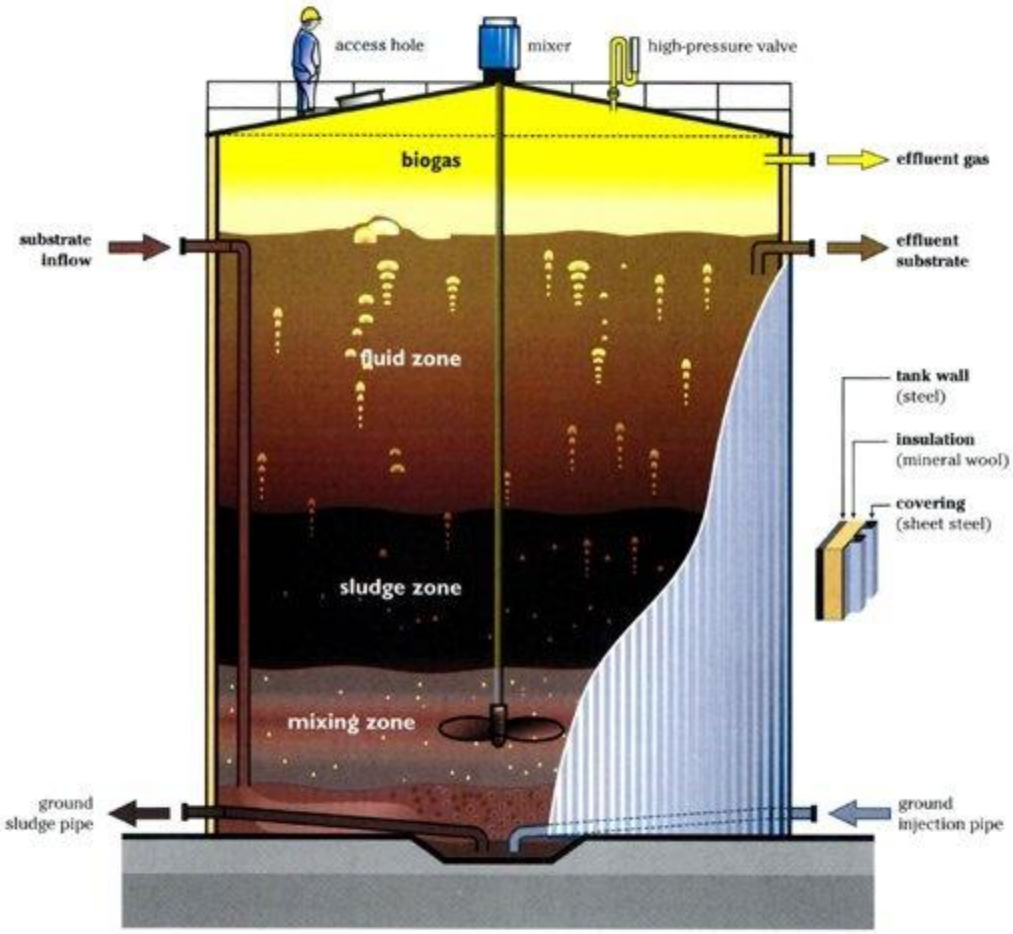


Figure 11: Sludge Digester
(Darling)

Some companies have built and manufactured some of these systems already. Community Power Corporation has a number of biomass powered digesters, including a digester that is small enough to be trailer or skid mounted and weighs about 1,500 kilograms. This specific type of digester comes in a variety of modules rated from 5-50 kilowatt hours of electrical power and 5k-500k BTU per hour of thermal energy. The fuel for this digester is listed as wood scraps, forest and agricultural residues while the fuel conversion is approximately 1.5 kilograms of wood for every kilowatt hour. This type of reactor is listed as the “Biomax Power

System" (Figure 12), and combines thermal and electrical energy and runs on a variety of fuels, usually plant-based waste (scrap wood, corn husks ect.), which could be integrated into a building setting relatively easily (Biomax Power System).

Figure 12: Power System
(Biomax Power System)

Of course, the large scale digesters used mostly in agricultural settings are extremely impressive and more efficient; however this technology comes at a price. The United Kingdom's first biogas plant processes 75 kilotons per year of food waste and animal manure and generates electricity and pipes hot water for the local community (Technology in Action:UK biogas pioneer on solid ground.). In the United States, many of these large scale facilities are being used to extract natural gas from cow manure. Although this may sound like an odd way to purvey energy, the payoff is worth the pay back, although a major problem for most farmers is the initial costs of such facilities. Micrology, a company designing such facilities, has plans for a new digester near Stephenville, Texas which has the expectations to fully pay back for the initial cost in less than three years. This facility at Huckabay Ridge will have eight 916,000 gallon digesters which all together are capable of processing the manure of 10,000 cows. This plant will churn out an estimated 1 billion square feet of biogas a year. This gas, methane, is valued at about $4.6 million for a year's worth, and the facility itself costs 11.5 million initially (Kanellos). However, most of the digesters used in a farm setting are only large enough to power the farm itself. Larger facilities will require the ability to sell excess power back to the grid, otherwise initial costs will not be made back as quickly as designers intended. However, these large scale farm digesters have an ample source of biomass and are extremely efficient in these larger settings. Digesters can be made small enough to fit in a backyard, on a trailer, or large enough to process incredible amounts of biomass, which makes this alternative energy extremely versatile and applicable to a variety of situations, which looks promising for its continued development and integration into our fuel economy. Applying these digesters into a dormitory building could prove promising and was investigated.

Wind Energy

Windmills are one of the few electricity generation methods that can be used on both a large and small scale. Turbines can be made as small as 20 watts and as large as 5 MW. Even with this flexibility electricity from wind accounts for only 13,326 MW of power in the United States, enough to power 3.2 million houses. 0.3% of the total electricity produced in the United States is created by wind turbines (Werner). Wind power is also a renewable energy source that has no carbon emissions.

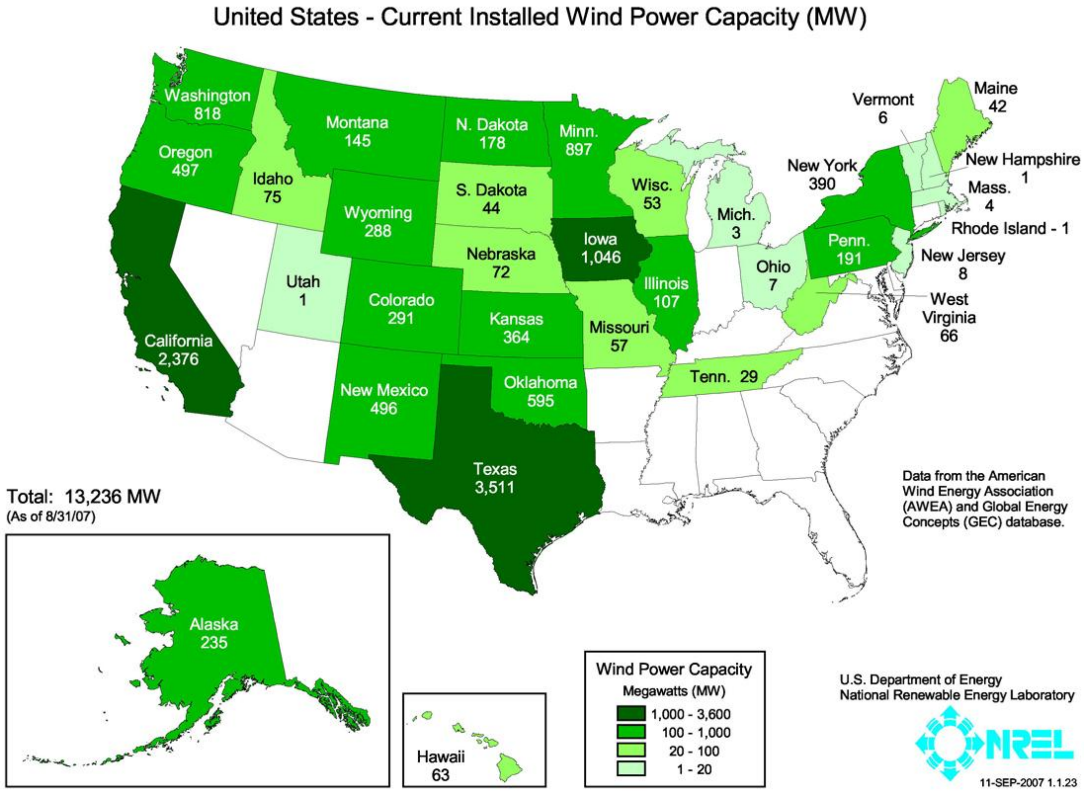


Figure 13: Current Installed Wind Power
(DOE 2007)

Wind generated electricity accounts for such a small percent of the total electricity generated because it is not a reliable source. Because the wind doesn't blow all the time the turbines are only running 60-80% of the time and when they are running they are only producing 30-35% of their maximum power on average. Wind turbines are theoretically 59% efficient when realistically they are only 35-40% efficient at best (Werner).

Electricity can only be produced by the wind when it is blowing between 3 m/s to 40 m/s (6.7 mph to 89 mph). Wind speeds below 3 m/s are not fast enough to generate the lift needed to turn the turbine blades, and at speeds above 40 m/s there is the possibility of mechanical failure (Werner). To be able to get anything out of a wind turbine average annual wind speeds must be no lower than 9.8 mph. As seen in Figure 14, the best locations in Massachusetts for electricity generation from the wind are along the ocean.

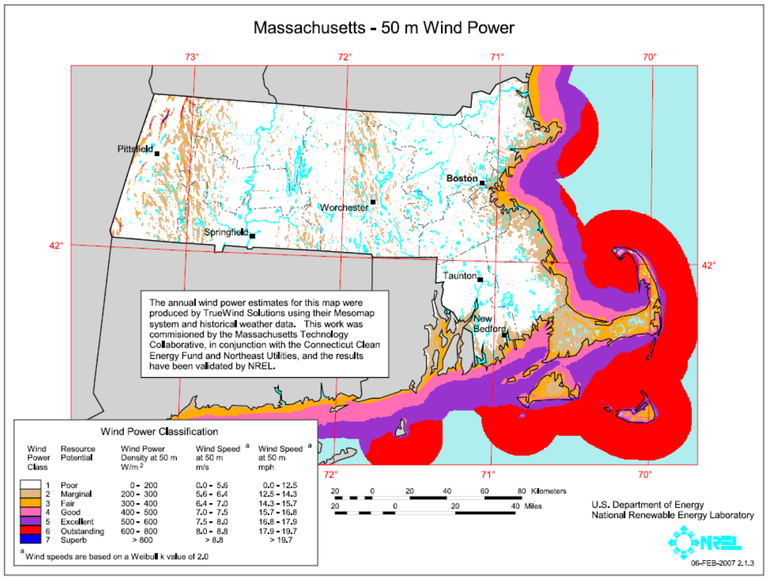


Figure 14: Massachusetts 50m Wind Power
(DOE 2007)

Although wind power may not be the most reliable source of energy it is one of the least expensive. At $1,600-$2,000 per kWh produced and an operating cost of about $52 per MWh. Most of these costs, about 70%, are due to capital (Fitch). According to the United States Department of Energy electricity from wind turbines only cost the consumer $.04 to $.06 per kWh.

One example of wind generated energy is in Princeton Massachusetts. A paper by Jonathan Fitch evaluates the towns plan for the wind turbines. The town of Princeton will be installing two 1.5 MW or 1.65 MW turbines. These two turbines are expected to produce 9 million kWh of energy. These two turbines will offset 11.6 million pounds of carbon dioxide that would otherwise be produced by fossil fuel plants (based on an EPA estimate of 1293 pounds of carbon dioxide produced per MWh). This paper also talks about many of the issues people have with wind turbines. One issue is that people worry that ice will form on the blades and on the towers of the turbines and will be thrown, possibly injuring bystanders who happen to be in the area. Mr. Fitch writes that the new wind turbines have automatic shut offs that will turn the turbines off remotely if ice is sensed. Many people also worry about noise from the wind turbines. After testing it was found that the new turbines will be a little louder than a whisper at a distance of 2000 ft, this is excluding background noise such as wind, leaves and animals (Fitch).

Wind power on a small scale can lower a house's electricity bill 50-90% depending on the size of the turbine. A typical Massachusetts house uses about 94,000 kWh a year or about 780 kWh a month. To make a considerable contribution a 5-15 kW wind turbine is needed. The typical size a single house would use is 10 kW. At this size it would cost about $32,000. In Massachusetts extra electricity that is created can be bought by the state at a cost of three to four cents per kWh and can be bought back at a price of 1.9 cents per kWh (Massachusetts 50m Wind Power).

Photovoltaic Energy

Solar energy is another attractive alternative to polluting fossil fuels; however it too has limitations. Solar energy can be harnessed in many ways, including photovoltaic cells to produce electricity, or mirrors to reflect and concentrate the sunlight to harness its thermal energy. Although solar is attractive, it does not comprise a major part of our nation's total energy production. In 2006, renewable energy contributed only 7% to our nation, with solar energy as 1% of that 7% division, or .15% of our nation's total renewable energy consumption, at .070 Quadrillion BTU's (Energy Efficiency and Renewable Energy: Ethanol). Although these numbers may seem insignificant, there was a 6.5% increase in solar energy consumption from

2005-2006. In addition, each kilowatt of PV-produced electricity annually offsets up to 2,300 kilograms of carbon dioxide, 16 kilograms of nitrogen oxides, and 9 kilograms of sulfur oxides (Environmental and Energy Study Institute). With these facts it is clear that solar energy deserves to be explored and developed, and with advancements in the field solar energy can become a cheap and efficient alternative to fossil fuels and an important step towards a green fuel economy.

The most common application of solar energy utilizes many tiny solar cells combined into something called a photovoltaic module and photovoltaic array to convert sunlight to electricity. They produce DC current, and can vary in size to power anything from a calculator to a building or even to a large scale solar power plant. Solar cells work by converting light energy, or photons, into electrons to create a voltage potential to power appliances. Solar cells are comprised of a front contact, a back contact, and a semiconductor material sandwiched in between. The semiconductor has an n-p-n junction, and allows light photons to knock electrons loose and flow through a circuit (Knier). An illustration is shown below:

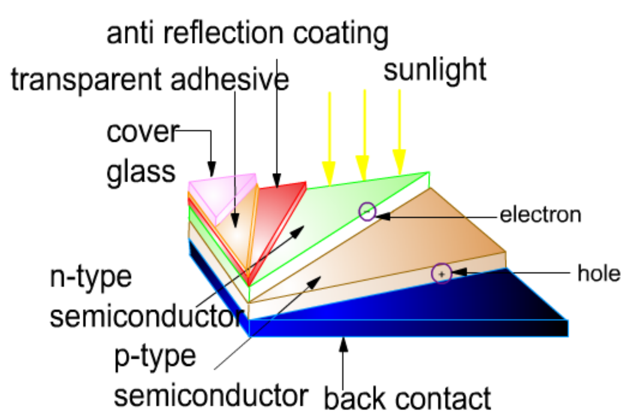


Figure 15: Solar Cell
(ThinkQuest)

In general, the larger the array is the more sunlight it can catch and therefore the more power it can create. Currently, solar cells have an efficiency of around 10%, meaning that 10%

of the irradiated light energy is converted to electrical energy. This is a low efficiency, however through other methods of collecting light the efficiency can be boosted greatly.

One such method is the use of multi junction solar cells. In this configuration, the solar cell is able to collect a larger portion of the solar bandgap. The bandgap is the minimum energy needed to move an electron from its bound state to its free state. In the typical multijunction cell, individual cells with different bandgaps are stacked on top of one another. It is configured so that light falls on the cell with the highest bandgap, and then transfers to the cells with the lower bandgaps. This allows the cell to absorb a larger spectrum of sunlight, and therefore absorb more energy. Much of today's research in multijunction cells focuses on gallium arsenide as one (or all) of the component cells. These cells have efficiencies of more than 35% under concentrated sunlight. An illustration of how these multijunction cells function is shown below in Figure 16.

Multi junction cells use the top cell to capture the high-energy photons and then pass the rest of the photons on to be absorbed by lower-bandgap cells. Figure 17 shows how this multijunction device has a top cell of gallium indium phosphide, then a "tunnel junction" to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide (Environmental and Energy Study Institute).

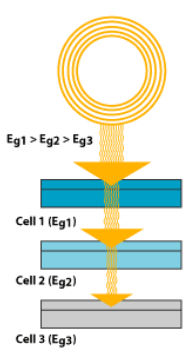


Figure 16: Multi Junction Cell

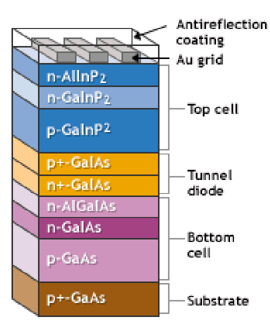


Figure 17: Multi Junction Cell Assembly

(Environmental and Energy Study Institute)

When this multijunction technology is then combined with solar concentrating technology, much higher efficiencies can be reached. In December of 2006, Boeing-Spectrolab achieved a world-record conversion efficiency of 40.7 percent under concentration, and an efficiency of 12 to 18 percent under one sun, establishing a new milestone in sunlight-to-electricity performance. This breakthrough may lead to systems with an installation cost of only $3 per watt, producing electricity at a cost of 8-10 cents per kilowatt/hour, making solar electricity a more cost-competitive and integral part of our nation's energy mix (Environmental and Energy Study Institute).

Solar concentrators operate on a very simple principle, which is if a lens is used to magnify the sunlight; more energy can be harnessed with the same area of solar cell. The lenses used with solar cells are called Fresnel lenses, and have been around for years but only recently applied to photovoltaics. Boeing-Spectrolab has achieved 236 suns under concentration with the use of a Fresnel lens, and the efficiency is continually rising (Elrod). The major problems with concentrator photovoltaics is that the sun can be magnified so much that surface temperatures of the solar modules go beyond the limits of the materials and they can actually melt. Therefore, the cells and lenses must be optimized to produce as much power as possible without causing damage to the cells and shortening their life. Also, the sunlight must always be perpendicular to the receiver, so the solar concentrator must track the sun as it moves across the sky. There are single and double axis systems in use. Single axis systems simply track east to west at 15 degrees per hour, and double axis systems track in a similar fashion but also take into account the slight lateral movement of the sun across the sky.

The thermal component of sunlight can also be captured to generate electricity in an indirect way. In fact, at Kramer Junction and Harper Valley, Ca, there is a collection of 9 solar-thermal-electric-generating systems that were installed in 1985 and are still operating reliably today. The system produces a total of 354MW of power, and although no new capacity has been added since 1990, they had produced more solar kilowatt-hours than the total installed capacity of PV in the US by the end of 2004 (Elrod). The design is a parabolic trough generating station, as shown in Figure 18.

Figure 17: Solar Concentrating Trough
(FPL Energy)

The parabolic shape concentrates the solar thermal energy on the pipe situated on the focal point that runs the length of the assembly and contains oil. The hot oil then goes on to produce steam which runs a conventional steam turbine to create electricity. Estimates suggest that in 2003, the energy costs of 10-12.6 cents per kilowatt-hour were achieved for these solar-thermal-trough designs and by 2020 with economies of scale costs of 3.5-6.2 cents per kilowatt-hour can be (National Renewable Energy Labs).

A similar approach to solar concentrating to boost power efficiency is the use of a parabolic dish to concentrate the sunlight onto a single receiving point, as shown below in Figure 18: Parabolic Dish.

Figure 18: Parabolic Dish
(Design News)

The above solar concentrator collects all incident light upon it and focuses it on the single collector. This particular one powers a Stirling heat engine, which in turn creates electricity. There are two main types of Stirling receivers, direct illumination receivers, which directly heat the chamber of the engine, or indirect receivers, which use a working fluid to transfer the heat collected to the chamber of an engine not mounted on the dish. Most of the time the working fluid is liquid sodium, which is capable of retaining heat for hours after the sun goes down, allowing the station to continue generating power into the darkness of the night. There are plans to erect 2 very large solar generating stations in Southern California, each generating over 300MW. For comparison purposes, the total US solar consumption is currently (Energy Information Administration).

Yet another form of harnessing solar energy is called the "Power Tower" configuration. This application utilizes many, often hundreds, of reflecting mirrors called heliostats to reflect the sunlight onto a single point of a tall tower. The tower contains either a working fluid such as oil or liquid sodium to conduct the heat to a generating station, or just water that is converted to steam inside the tower directly. The first solar concentrating plant in Europe was just completed in December of 2005 in Seville, Spain, as shown below in Figure 19: Solar Power Tower.

Figure 19: Solar Power Tower
(Inhabitat)

The solar tower is 40 stories high, and uses 642 heliostats each with an area of $120m^2$. It currently generates 11 Megawatts (MW) of electricity without emitting a single puff of greenhouse gas. This current figure is enough to power up to 6,000 homes, but ultimately, the entire plant should generate as much power as is used by the 600,000 people of Seville, around 300MW (Shukman).

In the end, solar energy has unlimited potential. The solar energy resource in a 100-mile-square area of Nevada could supply the United States with all its electricity (about 800 gigawatts) using modestly efficient (10%) commercial PV modules (Environmental and Energy Study Institute). Although this is an unlikely scenario, the solar cells and concentrators can be spread around the country to produce local, on site power to buildings, and many locations are already integrating them into their power systems and grids. By simply placing a photovoltaic array on the roof of a building, electricity can be produced throughout the day, and stored in batteries for use overnight or on cloudy days. The DC current stored in the batteries is then run through an inverter to make it AC to power normal appliances around the home. These PV systems are relatively expensive, however many local power authorities offer incentives to reduce the initial cost of the systems to entice people to look into green power. Typically, PV systems cannot provide all of the power needed, however they can contribute significantly to the overall electricity used. In the future they can be coupled with electrolyzers to produce onsite hydrogen to power PEM fuel cells, or large solar stations can produce mass amounts of hydrogen and deliver it to homes through pipes, much like natural gas is today.

As time goes on research in the field is gaining funding and popularity, and the efficiency of the cells is rising as cost is falling. Currently, in the California market, where state incentives and net metering are in place, PV electricity prices are dipping below 11¢/kWh, on par with some utility-delivered power. The energy payback period is also dropping rapidly. For example, it takes today's typical crystalline silicon module about 4 years to generate more energy than went into making the module in the first place, and they have an expected lifespan of up to 30 years (Environmental and Energy Study Institute).

Hydrogen Energy

Hydrogen energy offers many advantages over existing fossil fuels that are widely used today. Hydrogen is a clean source of energy and is abundant on our planet. Fossil fuels such as coal, oil, and natural gas produce harmful emissions such as carbon dioxide, carbon monoxide, nitrous oxide, and sulfur dioxide. All of these are harmful to the environment, and carbon dioxide is one of the leading players in global warming. Hydrogen, however, can be used in hydrogen fuel cells to produce electricity with the only exhausts as water and heat. Fuel cells can be made in a wide variety of sizes for almost any application. They can power anything from a cell phone to a building, and will reduce the dependence on foreign fuels.

Although hydrogen is abundant on earth, it is rarely found isolated from other compounds. It is mainly found bonded to oxygen as water, or to fossil fuels as hydrocarbons. To obtain hydrogen in its pure form as H_2 either water must be electrolyzed or methane must be reformed with steam at high temperatures. Both processes require much more energy than the amount of energy contained in hydrogen. Furthermore, reforming methane into H_2 releases more carbon dioxide than simply combusting methane. Also, methane has 4 times more energy than hydrogen, meaning that 4 times more hydrogen is needed to perform the same tasks methane does. Also, hydrogen is simply an energy carrier, not an energy source. Energy still needs to be put into it to split water, for example, and then be converted back to electricity or combusted to release the energy stored.

A hydrogen PEM fuel cell works by taking in the reactant gasses hydrogen and oxygen or air, and converting them to electricity. Upon entering the fuel cell, hydrogen contacts a catalyst, typically platinum, and is split into electrons and protons. The ionomer Nafion in the membrane electrode assembly only allows protons to pass through, and forces the electrons to travel around, where they are captured and directed through wires to run a load. After they travel through the load they are brought back to the other side of the fuel cell, where they combine with the protons to form a hydrogen atom once again. Oxygen or air is then introduced and water is formed which exits the cell. The entire process is very efficient at producing electricity, above 50%. This high value is due to no moving parts, and the only loss occurring in the form of heat. A small 1 inch by 1 inch PEM fuel will produce around 1 volt under no load, however when they are stacked the voltages of each cells adds. So, a 100 stack fuel cell assembly will create 100 Volts. The area of the fuel cell determines the voltage drop as load increases, so the larger the area, the more current the fuel cell can output. A diagram of how a PEM fuel cell functions is shown below in Figure 20: Hydrogen PEM Fuel Cell.

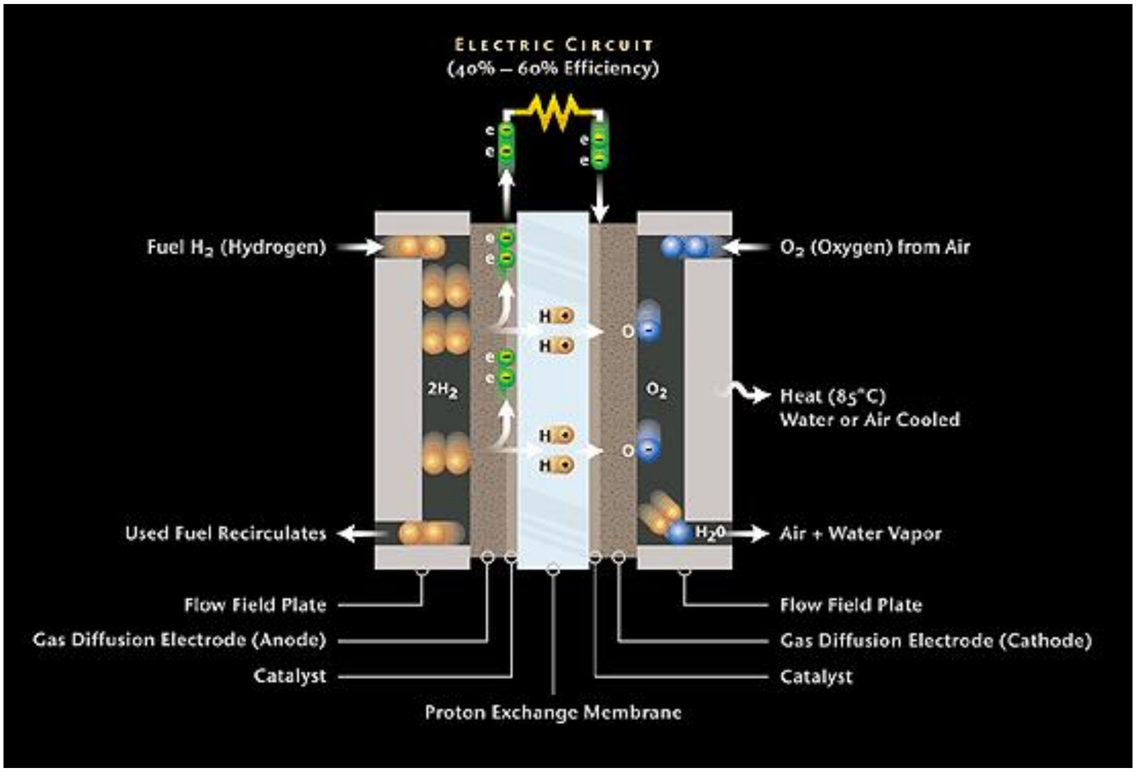


Figure 20: Hydrogen PEM Fuel Cell
(Micro-Vett)

Standing alone, hydrogen fuel cells face many challenges, but when they are combined with other renewable technologies, they become an integral part of the alternative fuel market. Hydrogen fuel cells have the ability to power vehicles of all sizes, from small sports cars to large trailers. The electricity they make is clean, and as long as the hydrogen they require is produced in a clean manner, they create no harmful emissions.

There are many arguments over the fact that hydrogen is currently produced largely by reforming methane with steam, and there are still large amounts of CO_2 produced. The alternative way of producing hydrogen is through electrolysis, in which electricity is sent through water to split it into hydrogen and oxygen. The problem is the electricity largely comes from existing coal power plants, so although the fuel cell is clean, the hydrogen fuel is “dirty.” Simple thermodynamics and experience show that processes which involve such a large increase in the free energy are with present technologies thermally inefficient, relative to the increase in free energy, even though electrolysis is the most efficient at 70% (Shinnar). This is true, and in order to create a stable green environment we must move away from fossil fuels and our dependence on foreign countries for energy.

Despite the fact that the processes are inefficient, if clean renewable energies are used, the losses are partially nullified. For example, if solar energy is used to electrolyze water, the losses in electrolysis are negligible because the source of fuel is the sun, which is plentiful. The same goes if the electricity comes from wind power, as the wind power is a clean efficient source of energy. A new method of hydrogen production is looking more and more favorable, and that is hydrogen cogeneration with nuclear power. Large nuclear reactors can provide power during the day when the load is high and overnight when the demand for energy drops the reactors can continue to run at full power and the excess can become devoted to hydrogen production. This would allow for mass quantities of “clean” hydrogen to be produced and piped to refueling stations and homes across the grid.

After the hydrogen is produced, the issue of storage must be considered. There are many storage options, and each has its advantages and disadvantages. The simplest is compressed gas storage, where the hydrogen is just compressed and stored in a bottle for later use. More elegant liquid hydrogen storage systems cool the hydrogen to a liquid and allow more hydrogen to fit into a smaller space. However, hydrogen must be chilled to around -252 degrees Celsius. This requires a huge amount of energy, much more than can ever be obtained back, so liquid hydrogen storage does not make much thermodynamic sense. Metal hydrides involve bonding the hydrogen to metals that will release the gas once heat is applied, allowing a storage at room temperature. Carbon nanotubes also involve storage at room temperature by capturing the hydrogen molecules in small straw-like tubes. Storage is still an issue, however compressed hydrogen is by far the cheapest and easiest, and will most likely be the primary storage option until better technologies are perfected.

Infrastructure is yet another issue that must be overcome before hydrogen can be widely used. The problem is that without an infrastructure the technology cannot become usable by the public, but without anyone to use the infrastructure, it will never become established. The solution is found in fleets. With fleets of vehicles, such as delivery companies or mass transit, refueling can be monitored and scheduled, allowing for hydrogen stations to be established and guaranteed usage. In 2003 Iceland established one of the first hydrogen refueling stations to power hydrogen fueled mass transit buses. Iceland was chosen for the project in part because of its history of using alternative fuel, as 90% of its electricity is from geothermal springs or hydropower. That means the electricity needed to make the hydrogen can be produced cleanly (USA Today 2003). California is also on the leading edge of hydrogen refueling stations, as it is on the forefront of almost all alternative sources of energy. California currently has 25 hydrogen refueling stations in operation, with 10 more planned for construction. The stations provide service to the 179 fuel cell powered cars in the state (California Fuel Cell Partnership). With these advancements, public interest will grow as demonstration vehicles are driven by high ranking officials and hydrogen becomes a more viable energy source.

Hydrogen can be integrated into standalone building applications and can help boost efficiency and eliminate issues as shown below in Figure 22.

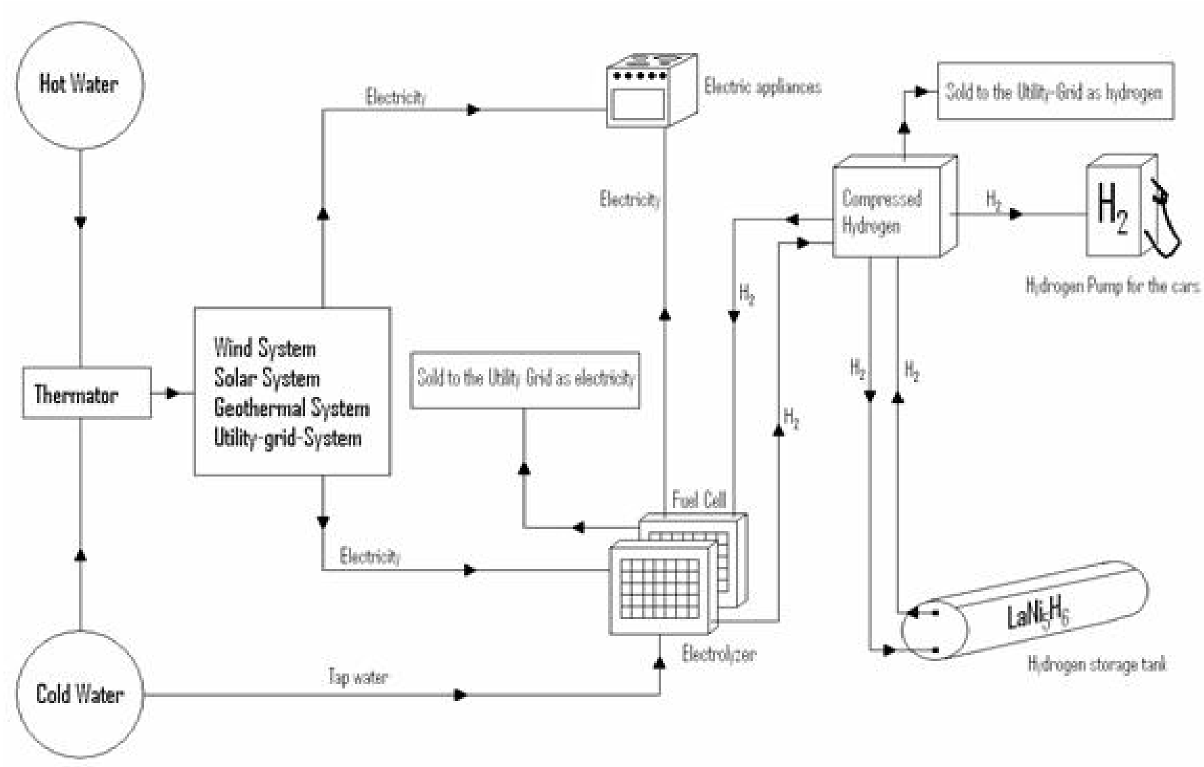


Figure 21: Icelandic House Hydrogen Infrastructure
(Kristjansdottir)

Utilizing hydrogen allows for the elimination of costly batteries in building oriented PV arrays, and provides numerous other advantages. The electricity produced by the solar array or wind turbine on site will go towards powering the appliances in the building, with the excess going towards producing hydrogen. The hydrogen is then used at night when the panels cannot provide electricity. The deep cycle batteries used are expensive and only have a lifetime of around 8.3 years (Richards and Conibeer). By eliminating them we introduce extra equipment like an electrolyzer and storage tanks which raise initial cost, however with the battery bank costing between $20,000 and $30,000 and needing to be replaced approximately every 8 years, the PV-electrolyzer system will be more economically viable in the long run compared to the PV-battery system. Also, while the cost of an electrolysis system is anticipated to decrease as the technology develops, the cost of batteries is not considered likely to decrease significantly over the next 10 years. This will enable the PV-electrolyzer combination to become more viable and economical (Richards and Conibeer). With all of these factors to take into account, an analysis must be performed to see whether it is beneficial to install PV systems on buildings when compared to other types of onsite energy production.

Green Engineering

East Campus Dormitory at WPI

A full write-up on the features and technologies employed by WPI's East Campus Dormitory may be seen in Appendix D, along with a table showing the expected energy consumption of the building. In addition, the LEED certification sheet for the building is included for reference.

LEED Certification

Buildings that utilize efficient and environmentally sound designs can become accredited by the Leadership in Energy and Environmental Design council. If a building meets certain criteria specific for each building type, they can become certified Leadership in Energy and Environmental Design buildings (LEED). The Leadership in Energy and Environmental Design Green Building Rating System™ is the nationally accepted benchmark for the design, construction, and operation of high performance green buildings. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on their buildings' performance. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection, and indoor environmental quality (USGBC). In order to become LEED certified, the building must meet certain requirements as well as score a preset amount of points, with point values being based on the type of building and the energy saving technique. For example, for an on campus building project, such as the East Campus Dormitory at WPI, optimizing energy performance is worth 10 points. Other areas such as ozone protection and water efficient landscaping are worth 1 and 2 points, respectively. The ways in which the building can meet these requirements is not specific, leaving room for innovation in all these areas, which creates a diverse collection of LEED certified buildings. The buildings can be rated certified or green (40-50% of total points possible), silver (50-60%), gold (60-80%), platinum (80%).

An example of such a building is the Doyle Conservation Center in Leominster, Massachusetts. The building is an LEED gold building and utilizes a solar PV array to produce approximately 20% of its total energy demand. The building also features automatic lighting controls and a computer controlled ventilation system. The ventilation system utilizes a geothermal well and heat exchangers, along with ERV units to boost efficiency. A total write-up of the building may be seen in Appendix C.

When considering onsite green energy production, a very important component is energy savings. Vertical axis wind turbines and solar photovoltaic panels typically have a low energy production and are dependent upon weather conditions, such as wind speed and cloud cover, and therefore vary in power production. Sludge digesters are dependent upon the number of inhabitants and the efficiency of the digesting unit. Therefore, due to the low efficiencies and low power outputs of most onsite energy production systems it is extremely important to lower the total energy demand of the building, thereby making it easier to match the needs of the building. Installing high efficiency appliances such as energy star rated appliances and compact fluorescent light bulbs can make a large impact on the total electricity demand, but more can be done during the design and construction phase of the building that will have a much greater and permanent impact on how much energy the building needs to maintain comfortable living conditions and a low energy load.

Zero Net Emission Buildings

Zero Net Emission Homes (ZNEH) are one such method of conserving energy. The theory is that the home or building is highly efficient at conserving and producing energy, however it remains connected to the grid. With this setup the building can draw power from the grid in a shortage of onsite energy production, and it can sell power back to the grid in times of over production. In this fashion the power grid essentially acts as a large battery system that enables buildings to be self reliant and also be there to help them when they fall short on production. To make this a reality the buildings must be well constructed with the goal of self sufficiency as a priority during design and construction. In the United States, it is estimated that commercial and residential buildings use 70% of the electricity produced (EIA). Since the USA primarily uses coal for electricity production, by making buildings energy efficient the amount of coal used and greenhouse gasses produced can be directly reduced.

Passive Solar Heating and Cooling

One engineering practice used in ZNEH's is the utilization of passive solar heating and cooling, which can come in many forms. In solar thermal water heating, water from the building can be pumped to the roof, exposed to sunlight and heated, then pumped back into the building to be heated to a temperature usable in a shower or appliance. By using the sunlight to pre heat the water, the water heater has to expend less energy to get the water to its final temperature because it has a higher starting temperature. The goal of passive solar heating is to maintain a comfortable environment within the building by utilizing the solar heat that falls on it, while minimizing the need for active heat and energy being expended. For passive solar heating to be effective, the location of the building and the sun's orientation must be accounted for to maximize efficiency. Solar heating takes advantage of the relatively low R-values of windows. The higher the R-value, the more the material will resist losing heat. For comparison, an efficient window might have an R-value around 2.5, while efficient insulation in the wall of a building might be between 30 and 40. By having these insulation "holes" in the walls, the solar heat can enter the house relatively easily and the insulation in the roof should hold it in as it rises.

During the cool season it is necessary to let in and store as much solar energy as possible to heat the building to a comfortable temperature without the addition of additional energy. During the warm season it is necessary to control the amount of heat gain and vent excess undesired heat through cross ventilation or by utilizing convection currents. Then, during the moderate seasons it is necessary to simply provide methods of compensating for slight weather variations as the temperature outside is likely a comfortable temperature for the interior of the building. This engineering practice is very effective when utilized properly. The sun will track across the sky at different angles at each latitude and each season and so the roof design must compensate for this. A good roof design will allow the sunlight in during the winter when the sun is lower in the sky, and block out the sun in the summer months when it is overhead. Once heat is added to the building, objects with high thermal mass, such as floors made of concrete, stone, or brick, absorb the energy and return it to the room as the air temperature falls overnight and convection between the floor and ambient air begins to take place. A typical design can be seen below in Figure 23.

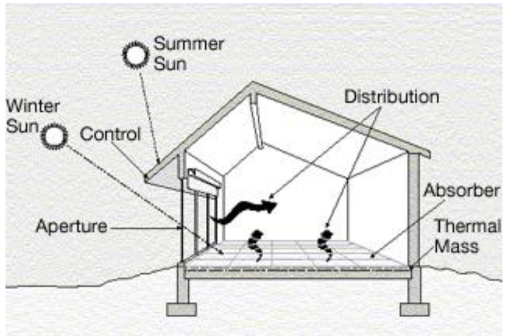


Figure 22: Passive Solar Design
(US DOE)

A use of solar energy for cooling during the summer comes in the form of a solar chimney. In this design, a chimney is erected next to the building that is to be cooled. The chimney is coated in a black, highly absorptive material so it gets extremely hot. This causes air in the tube to rise, creating a vacuum at the bottom. This vacuum end can be connected to an attic, therefore venting the attic into the air outside the house without the use of any pumps, motors, fans, or electricity. Another variation of the technology is when the chimney's vacuum side is connected to a tube that pulls in air and brings it below ground to cool the air. This cool air is then drawn into the building and cools it. A typical design may be seen below.

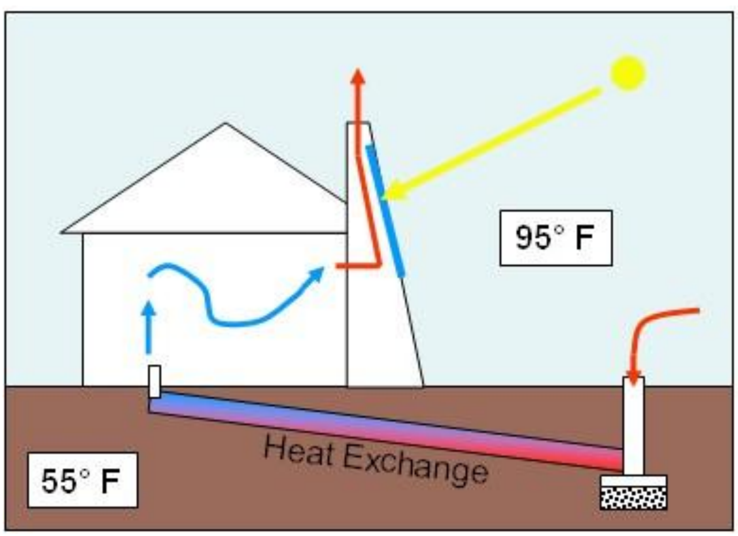


Figure 23: Solar Chimney
(US DOE)

Energy Recovery Ventilation

Energy Recovery Ventilation (ERV) is a very useful tool to decrease energy demands in the heating, cooling, and ventilation sector. An ERV is essentially a heat exchanger that will adapt the incoming fresh air to a temperature closer to that of the exiting stale air. By doing this in the summer, the cool exhaust air is used to cool the incoming warm fresh air, and in the winter months the warm exhaust air is used to warm the incoming cool air from outside. By using a Rotary Enthalpy Wheel the exiting air is mixed directly with the incoming air, so not only is heat exchanged, but so is humidity. This is an important key in the winter months as it will maintain comfort to a higher degree by maintaining a more humid, warmer air within the building. This works by using a rotating cylinder filled with a material permeable to air. As the wheel rotates between the incoming and outgoing air it picks up heat energy from one stream and transfers it to the other cooler stream. This works much like hot water heat recycling, which can save up to 60% of the heat energy that is normally wasted down the drain. This technology works by exchanging the heat between the hot waste water from a shower or dishwasher and the incoming cold water.

Cool Roofs

Another practice of keeping cooler temperatures in a building utilizes cool roofs. Cool roof's are typically painted bright colors or composed of a highly reflective surface to reflect the sun's energy back into the sky instead of absorbing it and adding more undesired heat to the building. A roof's reflectivity is a property that is measured on a scale from 0 to 1, where a roof rating of 0 means it absorbs all sunlight that falls on it, and a roof with a rating of 1 reflects all sunlight. Typical asphalt shingled roofs have a rating of .10, while typical asphalt shingled cool roofs have a rating of .35 which can decrease the buildings total cooling energy use by 7-15%

(National Renewable Energy Laboratory). In addition, cool roofing materials typically do not cost any more than standard roofing materials and so there is no worry about a payback period, it is simply an instant savings.

Superinsulation

Superinsulation techniques allow for a drastic reduction in the energy used by a building. A superinsulated home utilizes very high R-value insulation, typically R-40 in the walls and R-60 in the roof. In the insulation industry R-values and U-values are ways to rate the performance of the insulating material. The R-value is used to rate the energy efficiency of a single component, such as the glass plate in a window assembly. The U-value is used to rate the energy efficiency of the entire window assembly, taking into account the 2 panes of glass and air gap in between. Similarly, the U-value can be used to rate an entire building's energy efficiency by combining the entire assembly of windows, walls, and the roof energy performance. The R-value is a way to describe how much the material resists heat loss, while the U-value describes how much heat the material allows to pass through it. The process for converting between R and U-values is (1/R-value = U-value). This method of analyzing a material's performance is critical when designing energy efficient homes and superinsulated buildings.

A superinsulated home requires very little backup heat and is primarily heated by the waste heat generated by appliances and the body heat of occupants. This technique works very well however great attention must be paid to the design and construction details. When this technique is combined with other technologies such as hot water heat recycling and ERV systems, the building can use a fraction of the energy a normal one would consume and not at a much higher initial cost to the owner. Also, using triple glazed windows can greatly reduce the loss of heat during the winter months. This concept has been implemented in Germany and has received much support. The German "Passivhaus" has proved that the concept works and is a feasible design. A diagram of the superinsulation concept can be seen below in Figure 25.

.

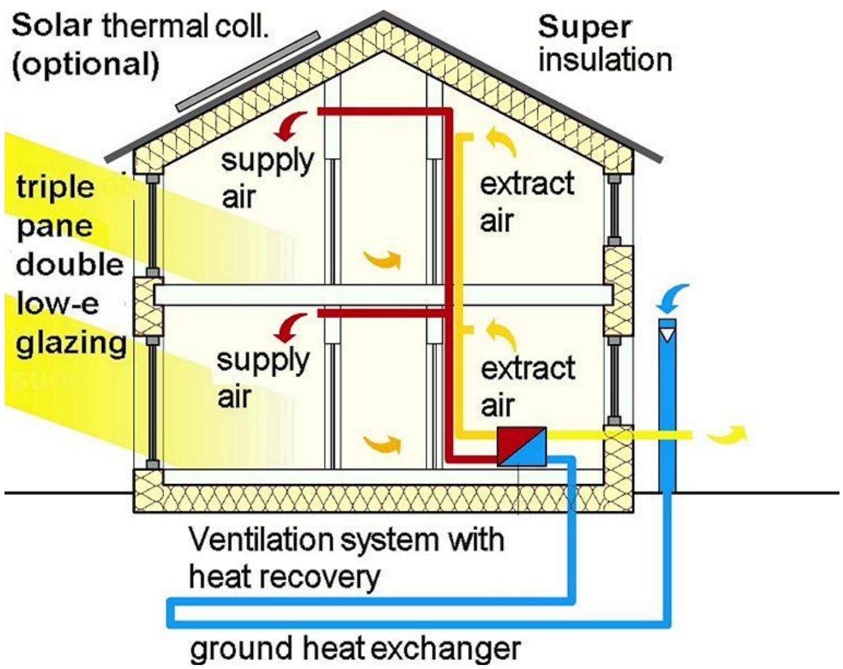


Figure 24: Superinsulation
(US DOE)

Energy Efficient Lighting

While it is very important to save energy in terms of heating and cooling, it is also important to save electricity usage. Up to 22% of electricity used by a building is strictly for lighting. By utilizing solar light tubes and fiber optics, it is possible to drastically reduce electricity usage within a building. Standard incandescent bulbs are extremely inefficient as much of the energy used is converted to heat. By using Compact Florescent bulbs (CFL) bulbs, the electricity usage is cut by about ¼. In addition, solar light tubes allows the sunlight that falls on the roof of the building to be channeled down into the interior of the building so the electricity used for lighting is even further reduced. By utilizing fiber optics the sunlight can be piped to virtually any spot in the building and therefore greatly reducing the electricity used. The technology used tubes with extremely high reflectivity on the interior to minimize losses and allow the natural free sunlight to replace costly electricity. While this technology only functions during the day it is useful for getting sunlight to closets and other places that window light can't reach.

All of these technologies can easily be integrated into a building if it designed with these criteria in mind. Using most of these concepts will not increase the initial cost of the building and merely require a different choice of materials and a slightly altered design. For instance, by utilizing passive solar heating more efficiently with triple glazed windows and superinsulation, the winter heating bills will be lowered. By utilizing CFL light bulbs, solar tubes, and energy star rated appliances the electricity bill will be lowered drastically. By installing an ERV system integrated with geothermal heat pumps the heating and cooling demands will drop an incredible amount. If hot water heat recycling and solar water heating is used the need for additional heating almost disappears. There are buildings that are in use today that use these efficient technologies and they have dropped their energy requirements by up to 85% (Gifford).

Passivhaus Designs

The German Passivhaus uses almost no energy for heating and cooling, and has only minimal electrical bills due to its high performance design. The designs are a great way to bring all of these design and construction methods together under one roof and show how they can all work together. Typical buildings in Europe have an insulation U-value of .25-.35 $W/m^2/K$, while the Passivhaus designs have a U-value under .15 $W/ m^2/K$. The energy efficient designs utilize southern facing windows to heat the buildings, while standard buildings rarely take the orientation of the windows into account. In addition, the windows of Passivhauses will not have a U-value exceeding 0.8 W/ m^2/K, while typical buildings can contain windows with U-values of 1.8-2.2 W/ m^2/K. For the energy efficient heating and cooling to function efficiently the buildings must also be very airtight. This allows for small variations in temperature with little energy input. An efficient building must have an air permeability value of less than 1 $m^3/hr/m^2$ @ 50 Pa, while standard buildings have an air permeability value 7 to 10 times higher. Consequently, the high air permeability factors defeat the purpose of installing ERV systems because much of the energy that is recovered by the systems is lost immediately. Also, although the ERV systems are very efficient at exchanging heat, the amount of energy required to heat and cool inefficient buildings is far greater than the ERV systems can provide. Also, Energy Star appliances play a crucial role in Passivhaus buildings, while other types of buildings typically aren't concerned with energy saving. By utilizing all of these technologies and standards, Passivhauses typically achieve a total energy demand for space heating and cooling of less than 15 $KWh/m^2/yr$. Standard buildings achieve a total energy demand for space heating and cooling of around 55 $KWh/m^2/yr$. (PassivHaus UK). This allows for a savings of around 27% on just heating and cooling demands. Energy efficient designs do incur a higher initial cost to the buyer; however the payback period is very short and worthwhile.

Overview of Technologies not Applicable to WPI East Campus Dormitory

Nuclear

Nuclear energy is the most efficient and powerful alternative energy that is in use today. However, the components necessary to harness nuclear fission restrict design concepts to larger scale applications. On the other hand, many new designs have been developed to make nuclear energy safer and smaller. The smaller designs that could possibly fit into a dormitory building are all being developed and tested; these designs have not been proven yet. Most of these nuclear power plant designs will not be used for quite some time, and total integration into the power grid could take years. The older designs will remain, as replacing them will also cost entirely too much, therefore only new applications could possibly employ the use of the new nuclear plant designs. The transportation and storage issues associated with nuclear waste are also a concern limiting the widespread implementation of nuclear energy. Analyzing the possibility of integrating a reactor into a single building will produce much more power than is needed and will not be worth the cost of installation and maintenance; it will be a waste of resources. The regulations placed on nuclear plants also require revisions to accommodate smaller, safer nuclear units, yet another obstacle for nuclear energy. A reactor powering an entire campus rather than a single dormitory is more feasible, but still extremely expensive. In light of these realities, nuclear power will not be considered as a possibility for the East Campus Dormitory application.

Hydrogen

On the surface hydrogen technology seems very promising. It has a high conversion rate of hydrogen to electricity, and the portability and modularity of the systems is enticing. However, when the technology is actually incorporated into a building's infrastructure, its weaknesses become clear and abundant. While the individual fuel cells are very efficient, the method of obtaining the hydrogen energy carrier is very inefficient and costly. Every step in the hydrogen process involves a loss of energy. Electrolyzing water takes a large amount of energy, and once the hydrogen is created it must be stored in a tank, where it slowly permeates the tank and results in daily losses. Then the hydrogen is fed into the fuel cell, where it loses energy again while it is converted to electricity. From here the electricity can be used or stored in batteries, where another loss occurs. In the end, the amount of electricity recovered is far less than the electricity initially supplied to electrolyze the water. By simply using the initial electricity to run the appliance or even store it directly in a battery, the major losses of the hydrogen route can be avoided. The only advantage the hydrogen technology provides is a simpler cheaper way to store the energy, however it comes at a cost of efficiency. Also, for a viable hydrogen infrastructure to be established, all of the natural gas pipelines would have to be changed, the seals and fittings would have to be replaced, and the pumps currently used would need to be swapped for higher pressure compressors. In theory the hydrogen can be produced onsite through solar PV or wind power, however these technologies would already be stretched to their limits and instead of losing energy by converting water to hydrogen, the building would see a much greater benefit by simply connecting the solar panels or wind turbines directly to the main power of the building. For all of these reasons it has been decided that hydrogen is not a sensible energy source for this project. With the goal being a sustainable building, only the most efficient energy production system must be chosen, and hydrogen fuel cells have too many problems at the present time to be considered a good source of onsite energy.

Overview of Technologies Applicable to WPI East Campus Dormitory

Solar Photovoltaic

Solar electricity is very applicable to almost any building in any setting and is a simple method of onsite energy production. The main problem with this technology on a small scale is it is too inefficient. On a larger scale the effect of low efficiency can be alleviated as many modules are connected together. With a typical efficiency of 10-15%, with the most efficient being 18-20%, it is not sensible to use this as a primary source of electricity for any small scale application. In trying to make a self sustaining building, the only area to place solar panels is on the roof, which is typically too small to see any significant production of power. With the average insolation of the Worcester area being 3.58 KWh/m^2/day, and the efficiency of a solar panel being 15%, only .537 KWh/m^2/day becomes electricity on a sunny day. A calculation of energy production is shown below.

$$E = \left(.537 \frac{KWh}{\frac{m^2}{day}} \right) (7000m^2) = 3759 \frac{KWh}{day}$$

This shows that if WPI's East Campus Dormitory's roof was completely covered in solar panels, it would produce 3759 KWh/day, or 1.4 MWh/year, which is a little over half of the building's projected annual electricity consumption of 2 MW as seen in Appendix D. This is assuming that the building's entire roof would be covered in panels, which is impossible. The solar panels must be oriented South and must be tilted at an angle to obtain their highest efficiency. By playing them in arrays at angles, one array will shadow the array behind it, therefore adequate spacing must be given between rigs. While it may seem like an attractive technology, it does not make sense to apply it on a small scale for self sufficient buildings that are limited by small roof areas, especially when there are other applications such as vertical axis wind turbines which are far more efficient than solar PV panels.

Biogas Production by Anaerobic Digestion

Biogas fuel from human waste is not a new topic and has been researched and implemented in many different applications. The most widespread uses of these types of waste digesters are in rural settings in developing countries, where the establishment cannot be powered directly by the grid and must be fueled by conventional methods such as the burning of firewood. The solid waste left over from the process also provides excellent fertilizer for surrounding gardens or farmland for a superior yield of produce. The other large market for these digesters lies within a city's wastewater and sewage treatment plants. These facilities already collect the fuel needed, so the much larger digesters can be built right into the treatment process with minimal construction costs for storage and piping. Also the digesters reduce the amount of effluent to be disposed of. This effluent is usually used as fertilizer, either dried out and shipped or used on site. These applications seem to yield the highest efficiency of cost versus biogas output. However, we needed to adapt these current designs to fit our application of a single building; a dormitory housing 250 students.

Case Studies

A Rwandan prison has been outfitted with a human waste digester system by the Kigali Institute of Science and Technology, in the capital city of Kigali, which has been implementing bio-digesters all over the country. The prison houses 6,000 to 10,000 inmates; however, the waste from only 1500 inmates is used to feed the biogas system. This 150 cubic meter fixed dome digester produces fifty percent of the cooking gas needed for the entire prison. This cuts in half the firewood bill, which amounts to about $22,000 yearly (Okafor). These digesters are built underground, where they are out of sight, and more importantly; the smell is contained. This system also solves a common hygiene problem with sewage which plagues most third-world countries (Richard).

Digesters of this type are very basic in design, which originally came from China and were adapted by a Tanzanian engineer working in Rwanda. A 100 m^3 tank can store 20 m^3 of biogas, but may generate up to 50 m^3, therefore the gas must be consumed regularly each day. When this system provides cooking gas, this is not a problem. The systems are bee-hive resembling, being built on a circular concrete base using clay or sand-cement bricks. At the top of the structure there is a half meter man-hole. The biogas is stored on this upper part of the digester, of course the interior and exterior are well plastered to ensure air-tightness. The gas is piped from the hole at the top into the kitchens, where the methane-carbon dioxide gas mixture is burned. The wastewater is pumped into the digester using closed channels, decreasing the odor The success at this prison led to five of the country's largest prisons now planning to use bio-digesters, which are either in-construction or operational. The internal workings of the digester are completely maintenance free. This design utilizes a compensating chamber which houses extra bacteria for improved digestion and superior gas production. As gas is pumped out of the digester, the backflow pumps waste and bacteria from the compensating chamber into the main digester cavity, which mixes around the waste and bacteria, releasing trapped gas and creating optimal digestion conditions. Constant influent pushes effluent out of the digester into a stabilizing tank where additional digestion takes place for complete breakdown of the waste. From there the effluent is run through a unit for solid versus liquid separation. The solids are composted for three months and then used as fertilizer. Routine lab checks ensure that the effluent is not contaminated by any bacteria, viruses or worms (Wheldon and Judges).

These systems have been used extensively and with extreme success. A 500 m^3 system costs roughly 50 million Rwandan francs, which equates to less than $26,000. Of course a payment plan is in effect, which includes that the final five percent of payment is not required until after six months of complete and stable operation. These units are built to last 30 years, although much like anything else, it is recommended to “de-sludge” the digesters every seven years (Wheldon and Judges). The digester works rather simply; as long as the proper fuel is present, the anaerobic digestion will take place and methane will be produced. These designs are popular in these applications because they are relatively cheap, especially when savings are accounted for, and the design is simple and easy to maintain. These units also create jobs for maintenance workers, as well as save time and effort that was previously used collecting firewood (Brown). These types of bio-digesters are growing extremely popular in developing countries, especially as existing units continue to thrive with minimal problems.

The other popular third-world country design lies in simple rural home applications. The main designs change for every application such as climate, waste being digested (most use animal dung), and size. The larger of the bunch includes a Chinese model dubbed “Chinese Fixed Dome” which has over 6 million users as well as an Indian model, the “Indian Floating Cover.” These designs are more or less the same with a smaller intake tank leading into the main digester tank, where gas is piped from the top away to kitchens. The effluent is then led into another tank where it is disposed of. The only difference between these models is that one utilizes a fixed dome and the other a floating cover that will float in a direct relationship on the contents of the digester. The latter of these models has the capability to store more biogas as the cover is self supporting, therefore it will not exert any pressure on the gas itself. The fixed dome model is easier to build and maintain as the floating cover must maintain an air-tight seal throughout its motion (Watkins)

A smaller, more compact, residential model has been developed and is used throughout the Philippines. This model is for a 5 m^3 system, which is advertised to work best with pig and cow manure, but can be operated on any form of animal waste. The digester must be fed manure mixed with water in a one to one ratio and can handle up to 50 ^{L}/Day. The digester was designed to make the system as user-friendly as possible, it eliminates difficult to build parts, such as a concrete dome cover or any mixing system. This system can be built anywhere, eliminating piping problems. Of course this is a simple design which does not provide complete digestion or provide anything other than cooking gas. The effluent can be used for fertilizer; either as is in liquid solid form or it can be dried out to making handling the effluent fertilizer easier. However, for families with animals, the design virtually eliminates the cost for cooking gas and is relatively cheap and easy to build (Baron). Once again a simple adaptation of a larger scale digester to fit a certain application was designed and widespread implementation has resulted.

The large, municipal type digesters are by far the most efficient and most impressive of the designs available. These digesters have been designed for industrial sized wastewater and sewage treatment plants; therefore the amount of waste that can be digested is immense. Siemens as well as others sell a wide variety of products that can contribute enormous savings to waste disposal as the waste is composted as well as provide power to the plant using the biogas produced. This application’s loading rates and digester volume do not compare to the dormitory situation therefore these vendors advertised products will not be of any use in determining the output of this application.

Analysis of Dormitory Application

For our uses, a bio-digester needs to process and store the waste created from a 250 student dormitory. Using a simple analysis by comparing this application to other similar data, the outcome of such a system can be determined. The only way to find the actual outcome of bio-digesters is by a complete chemical analysis of the waste to be digested and a complete analysis of the digester conditions, i.e. temperature, ph, retention time and other relevant factors. Digester type also plays a major role in biogas production, mixing and temperature have a direct effect on the amount and quality of gas produced; however, maintaining these elements requires more energy which will decrease the output of the bio-digester (Bergamasco, Rizk and Tavares). Municipal sewage plants usually use mechanical mixers as the sheer amount of waste digested can produce more than enough biogas to satisfy the mixers energy needs (Greiner, M.E. and Smith)Using various sources and methods, we can estimate the biogas production possibilities of this particular application by assuming many of these conditions.

Due to the lack of a complete chemical analysis, several assumptions need to be made in order to approximate methane output. Firstly, most biogas from waste digesters of this type is roughly 60 percent methane and 40 percent carbon dioxide (Fontenot, Smith and Sutton) We also assumed that digestion is complete, as well as anaerobic and mesophilic (35 degrees Celsius). Greiner, M.E. and Smith have computed a basic formula using the assumptions and criteria listed above. This approach for calculating approximate biogas output deals with the amount of volatile solids (VS) and chemical oxygen demand (COD) of the waste being digested. Another source, McElvaney Associates Corporation, has determined a formula using only volatile solids information and digester size. Both of these estimations as well as simple proportions from actual human waste digesters were used to predict potential biogas production.

The (Greiner, Hein and Smith) technique was originally devised to determine potential biogas from animal waste in a farm setting. Comparing human waste to animal waste shows that a direct comparison between the two will not suffice for our purposes as the differences are too great. A multitude of sources were used for this comparison and it is clear that percentages of the composition such as total volatile solids, nitrogen, phosphorus, carbon, ash, and the differences in diets are not compatible for comparison ((Gustafson, Kenimer and Lesikar), (Schouw, Danteravanichb and H.), (Parker and Gallagher), (Fontenot, Smith and Sutton), (McElvaney Associates Corporation), (Were)). However, the factors for animal waste can also be computed for human waste. The first estimation is a simple relation of chemical oxygen demand, which provides an output of m^3 of biogas per m^3 of digestion volume. The equation is simplified into multiplication of pre-determined factors; (kilograms of COD fed daily)*(COD reduction)*(cubic meters of methane per kilogram COD) (Greiner, Hein and Smith). First we need to determine the amount of COD fed daily, which requires some variables that need to be calculated from the waste composition. Using an average of various wastewater and sewage data, we approximated these values as shown in Table 1.

Table 1: Volatile Solids and COD relations

	Gustafson, Kenimer and Lesikar	Meschke	Klass	Average
Total Solids	34.1 g/L	1250mg/L	2.2kg/L	
Total Volatile Solids	23.1 g/L	810mg/L	1.6kg/L	68.5%VS of Total Solids
Chemical Oxygen Demand	31.9 g/L	910mg/L	-	
Chemical Oxygen Demand: Volatile Solids	1.38: 1	1.12: 1	-	1.25: 1

Essentially in order to calculate the amount of COD that will be fed to the digester, we need two pieces of data according to (Greiner, Hein and Smith); kilograms of volatile solids per liter per day and the ratio of chemical oxygen demand to volatile solids. To find the amount of volatile solids, we need to approximate the amount of total solids that will be sent to the digester each day. The average human being will produce 154 grams of solids per day and 4.3 liters of fluids per day ((Niwagaba), (Parker and Gallagher), (Schouw, Danteravanichb and H.), (Geurts)). If we multiply these numbers by the 250 students in the dormitory, we can determine that about 38.5 kilograms of solids and 1100 liters of fluids will be produced each day. If 68.5

percent of those solids are volatile solids (percentage taken from Table 1), then we can assume 26.37 kilograms of volatile solids will be produced each day by residents of this dorm.

Using a method from McElvaney Associates Corporation we can calculate kilograms of VS per m^3 by simply dividing by the digester volume. We used several sizes to find the gas output. We then averaged the two different digester sizes. A simple proportion from the Rwandan prison system provides us with a digester size of 25 m^3 for the 250 student dormitory. A digester volume of 11.55 m^3 is supplied by a calculation from McElvaney Associates Corporation which takes into account retention time, which will have a value of 30 days as suggested from the same source. Averaging these two separate digester sizes, the end result is about 18.3 m^3. Using this as the digester volume, the end result is about 1.44 kilograms of VS per m^3. With a few conversion factors (.001 m^3 per liter and 1000 grams per kilogram) we converted the former factor of kg of VS per m^3 to grams of VS per liter; which remains the same number as the conversion factors cancel. This provided the first value of 1.44 kg VS per liter. Our second value is the COD reduction which is about 40 percent ((Klass) and (Fontenot, Smith and Sutton)). Finally our third value was determined as .375 m^3 of methane per kilogram of COD; assuming full digestion. This value was determined by a mass balance on the COD which can be used as anaerobic digestion has no external source of oxygen (Greiner, Hein and Smith). Therefore we now have our three components for the equation.

Using the above calculated figures, the first estimation yields 0.27 m^3 of methane for every m^3 of total digester volume. Assuming a 60 percent methane biogas, the total amount of biogas is 0.45 m^3 of gas per m^3 of digester volume, which multiplied by the digester volume equals 8.24 m^3 of biogas per day. This result has been derived from many sources and contains many assumptions; however, this is merely an estimate therefore the theoretical calculations provided a solid starting point in assessing the bio-digesters use in the building.

We can also perform a different, rough output estimation, however, this equation relied on actual data rather than assumptions. This data is supplied from Klass, using a calculated 0.313 m^3 of methane per kilogram of VS added. When we multiplied this by the 26.37 kilograms of VS per day calculated before, the calculation yielded 8.25 m^3 of methane per day. Once again assuming 60 percent methane the determined amount of total biogas is 13.75 cubic meters per day. This approach is extremely simplified, but has been derived from actual results from municipal sewage sludge digestion (Klass). Therefore, it will be averaged into the total estimation.

Another estimation is from McElvaney Associates Corporation, a method that requires only the amount of volatile solids in the waste, digester efficiency (assumed as 80%), and the biogas density at 65 percent methane (which McElvaney has calculated as 1 m^3 per 1.14 kg). This method multiplies the 26.37 kg of VS by the digester efficiency and the biogas density. This approach produces 18.5 m^3 of biogas per day. This estimate is higher than the previous two methods. This could be due to the simplicity of this result as it is a basic calculation which does not take into account many factors that will influence biogas production.

In order to widen the scope of the estimation we also used basic proportions from data gathered by simple biogas systems used in developing rural countries such as Rwanda and a prison biogas system located there. Although this approach may seem too simple, it illustrates an approximation from similar waste input and one of the most basic digester designs being used today. Two separate proportions were used, simply two variables related to digester output; number of people contributing to digester waste and digester volume. The digester volume of

18.3 m^3 will remain as the dormitory application size. These estimations are very basic, but once again provide a solid piece of the estimation as the data is backed by actual reported digester outputs. The values for all of the estimations and their respective techniques have been averaged in Table 2.

Table 2: Gas Output Predictions for 250 Students

Estimation Technique	**Biogas Yield per Day**
Greiner, Hein and Smith	8.24 m^3
Klass	14.38 m^3
McElvaney Associates Corporation	18.5 m^3
People to Digester Output Proportion	12.5 m^3
Digester Volume to Output Proportion	9.15 m^3
Average Output	**12.55 m^3**

This biogas can be used in a variety of applications, although it is usually used as cooking gas. One cubic meter of biogas can produce enough cooking gas to cook 3 meals for 5-6 people (Baron). The gas contains not only carbon dioxide and methane, but also water and hydrogen sulfide. The hydrogen sulfide can be scrubbed out of the gas by passing it through wood chips injected with $FeCl_3$ or through steel turnings; either way the reaction will form insoluble ferrous sulfide (Greiner, Hein and Smith). Removing the hydrogen sulfide is important to avoid corrosion problems, which can become extremely severe. Mobil Oil manufactures “Sorb Beads” which can also remove hydrogen sulfide and water vapor (Jones, Nye and Dale). The carbon dioxide will also inhibit the performance of the biogas. In small scale applications it is usually much easier to take the gas as it is and accept the losses, or the carbon dioxide can be scrubbed from the gas with sulfur (Watkins). Experience has shown that a 60-65% methane mix with CO_2 is potent enough to burn in all applications within a building.

Relating this output to the dorm building ignores many crucial factors such as pH levels, ammonia production inside of the digester, mixing and of course temperature. Theoretically the digester type could be similar to the Chinese-adapted models used in Rwanda which provide natural mixing by backflow and therefore will need no energy for a mechanical mixer. If a mechanical mixer is employed, mixing only 3-4 times daily is roughly equivalent to continuous mixing (Jones, Nye and Dale). Insulation of the digester also plays a major role in temperature conservation. Another factor to consider is where the digester is placed, whether in a building basement or underground which will also affect temperature. Recommended values for insulating the digester are R=10 for ground contact and R=20 for air contact (Jones, Nye and Dale). In order to estimate the amount of heating needed to maintain the digester at 35 degrees Celsius many elements including those above need to be determined. However, by briefly examining temperature trends in Worcester, an average temperature of 8.2 °C is expected (CityRating.com). When we compared Worcester's annual temperature to the average temperature of Ames, Iowa (9 °C, from Greiner, Hein and Smith) it is reasonable to assume a similar heating scenario especially because the heating method of digester does not vary greatly from design to design. From the data acquired in Iowa, it became apparent that in the colder months of the year the digester may require more energy to maintain its optimal mesophilic temperature than the digester will actually produce (Greiner, Hein and Smith). Although the digester in Ames is much larger than the dormitory application, a similar situation is probable. If the previous variables are ignored and the estimation is assumed to be actual output, the biogas will yield 161,800 cubic feet of gas per year, which converts to about 971 therms per year. This will only provide about 2.1 percent of the 46,646 therms per year of natural gas needed for the dormitory, as shown in Appendix D. Although in reality, the system would provide even less energy as it would need to heat itself, perhaps run a mechanical mixer, and chemical compounds could adversely affect the biogas output. In conclusion, it is safe to declare a bio-digester waste system in the dorm building would not provide enough energy for the cost and implementation of such a system, even assuming near optimal conditions for digestion.

Solar Water Heating with Drain Water Heat Recovery System

There are many options for heating water for use in a building. Conventional water heating uses natural gas to heat a tank of water from a temperature of around 40-50 °F to around 120 °F for use in showers, dishwashing machines, and washing machines. This method is extremely inefficient and has many energy losses. First, standard natural gas heaters have an energy efficiency of around .54 (Wilson). This means that roughly 1.5 times the amount of energy needed to heat the water must be combusted as natural gas. This means a higher cost to the consumer and more CO_2 is released into the air. By installing an "on-demand" or "flash" electric water heater with an efficiency of .95 (Energy Efficiency and Renewable Energy) an energy savings can be 35-40% can be seen annually.

Energy Analysis

As seen in Appendix D, there are 232 residents on 4 floors, with 58 per floor. With 232 residents it is estimated that 350 showers per day will take place in the building over the course of a day. This means an average of 1.5 showers per day, per resident, with some using the showers in the morning, at night, or both. An average shower using a low flow shower head consumes 2.5 gallons per minute (gpm) and lasts approximately 10 minutes, meaning approximately 25 gallons of hot water is needed per shower. This means about 8,750 gallons of water needs to be heated per day to satisfy the shower needs of the building. The demand posed by the sinks must then be addressed. A typical low flow bathroom sink consumes .5-1 gpm and the average low flow kitchen sink consumes 1-2gpm. If each apartment needs hot water through their sinks for 1 hour per day, that adds another 2,520 gallons per day. This is a high estimate, but it is more beneficial to have a system that can compensate for high loads so a shortage of water doesn't occur. This accumulates to 11,270 gallons of water per day, with 8265 gallons of water that needs to be heated to 115 °F. Temperatures above 115 °F in showers risk scalding and so it is a waste of energy to heat the water beyond this point.

Energy Efficient Water Heating System Design

To meet these needs, an extremely efficient water heating system has been designed for this project. The system incorporates solar thermal heating with energy efficient pumps, and a drain water heat recovery system. For the diagram of the system and a technical explanation of operation see Appendix B. When working at average conditions, the proposed system uses almost zero electricity to meet all of the hot water loads within the building. This is possible by using creative engineering using basic thermodynamic concepts. An evacuated tube solar water heating array was chosen as it is ideal because the tubes absorb solar energy and transfer it to the glycol solution running through it, but do not emit the heat back to the environment due to the vacuum. This allows for constant temperature inside the tubes and constant power generation regardless of the ambient air temperature. A glycol solution is used so there is zero risk of water being caught in the panel and freezing during the cold season, which would destroy the system. The following mathematical calculations may be seen in Appendix A.

The system provides for 20 shower stalls total, with 5 per floor, with each stall consuming 319 gallons of hot water per day. The demand posed by all of the sinks on each floor is equal to the demand of one shower stall per floor. This means that each shower stall consumes 27.3 KWh per day, with a total of 546 KWh per day for all 20 shower stalls in the building. Adding in the demand from the sinks and faucets, an additional 134.7 KWh demand is placed on the system for a total of 681 KWh per day. The innovative system proposed for this building incorporates an Apricus evacuated tube solar heating system combined with an 80 gallon insulated water tank and drain water heat recovery technology. A 150 tube array per tank provides 29.4 KWh per day per shower, and as stated before, only 27.3 KWh per day is needed. The key to this system is the drain water heat recovery technology. With this system, 70% or more of the heat from the drain water is recovered by the incoming cold water, adding approximately 21.5 °F to the water before it gets to the solar tank to be heated. This allows for an inlet temperature of 80.5 °F, meaning the solar array only has to add 34.5 degrees to the water before sending it to the showers. The system essentially heats itself the more it is used, which is ideal for high use applications such as this residence hall. As the demand for hot water goes up, so does the ability to produce hot water, so it is very difficult to overstress the system.

Since these calculations were done on yearly averages of solar insolation and yearly water demands, day to day fluctuations are bound to occur and demands will fluctuate. This system has overhead room built into it to allow for a daily increase of about 10%. If there is more of a demand than that, the system has electric on-demand water heaters built in line. They will remain switched off unless the demand exceeds 10% and they are required to activate. Electric on-demand water heaters have an efficiency of 95% as stated above, so essentially any energy that they use is directly given to the incoming water. Most systems are able to easily produce

2.5Gpm, which can fuel a single shower using standard cold tap water and a low flow shower head for an infinite amount of time. They are cheap enough to install 2 units per floor to be shared between the showers in case of emergency or cloudy days for extended periods of time. All of these calculations were done assuming the lowest efficiencies of all products on average weather days and average water consumption. This water heating system has enough headroom to accommodate almost any situation that it might encounter, and based on the yearly average solar insolation of the area, this system will only need approximately 1Kw of power which can simply tap off of the existing wind power system of the building to run its small, low power pumps to recycle the glycol fluid through the tube manifolds. The array would need a total of only 3420 ft^2 on the south facing roof, which is easily accommodated by the 6750 ft^2 available on that roof. Evacuated tubes do not need to be mounted at an angle on the roof, which saves roof space, makes the system more reliable, and eases installation greatly. Due to the tubular design the sun is always perpendicular to the tubes surface, and they will heat the glycol liquid no matter what angle the sun is at in the sky.

Geothermal Heating and Cooling

When analyzing the methods of heating and cooling the new East Campus Dormitory geothermal heat pumps and heat exchangers were chosen as the best method possible. Geothermal heating and cooling uses water from underground to heat or cool a building. This underground water has an average temperature of 55^0F in the Worcester Massachusetts area (Bloomquist). The way a geothermal heat pump works is by bringing water up from underground and passing it through a series of pipes. Once inside an electrically driven compressor and a heat exchanger concentrate the Earth's energy and release it inside the home at a higher temperature.

Ductwork distributes the heat to different rooms. During summer months when it is required to cool the building the process is reversed. The excess heat from the house is absorbed by the underground water and pumped back into the earth (California Energy Commission).

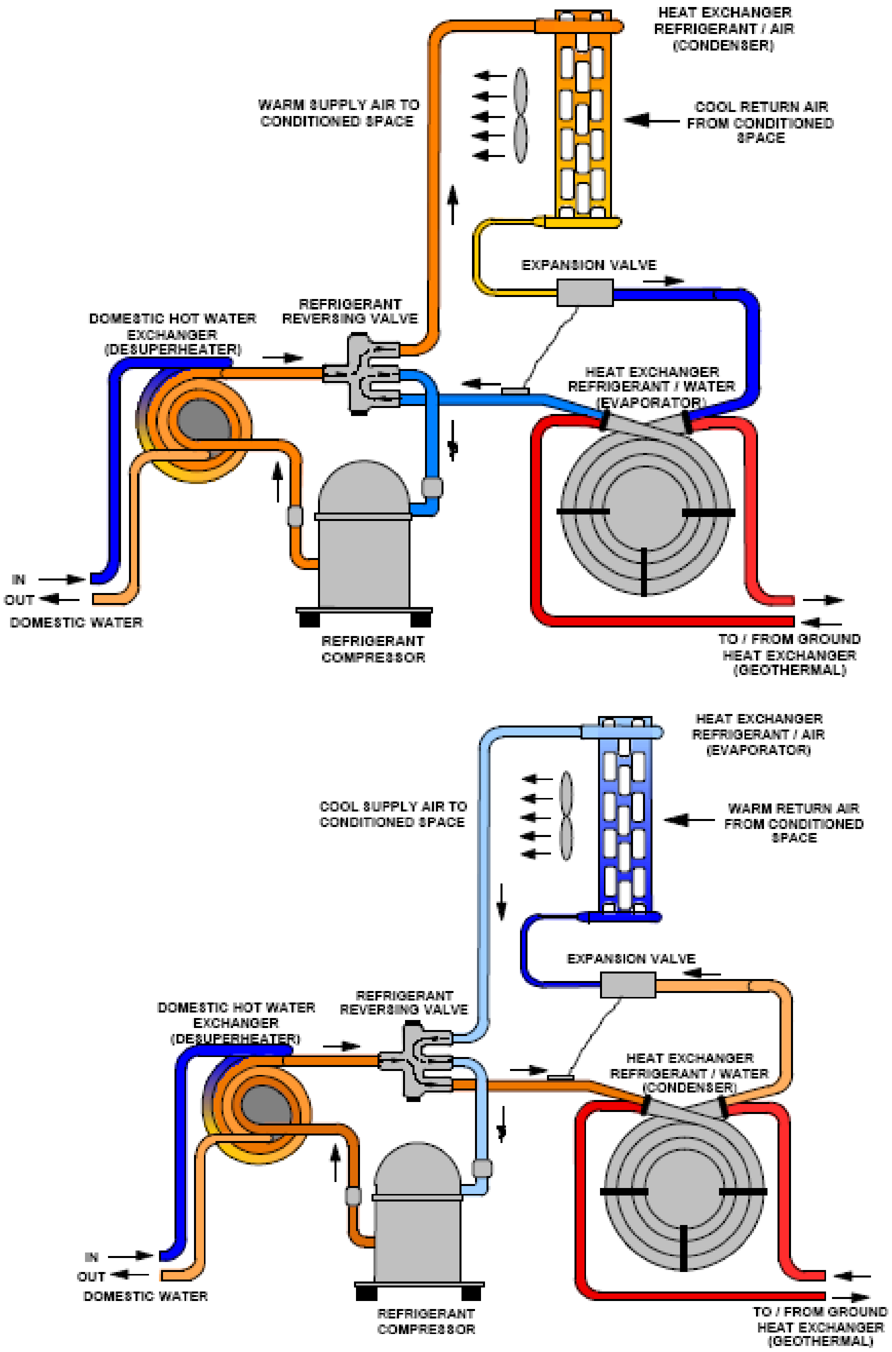


Figure 25: Geothermal Heat Pump Heating and Cooling Cycles
(J. Lund).

In the case of the dormitory due to the large area that is required to be heated and cooled it was decided that an open loop system would work best. An open loop system requires the drilling of wells to reach the underground water. The wells can be anywhere from 80 to 450 feet deep. The water is then pumped up to the building and the system works as explained previously.

It should be noted that the figures that are going to be used in the following calculations are from an apartment/condominium building of comparable size in Westminster, Massachusetts and was built in 1965. All calculations are expected to be 15-20% lower than stated here. The reason for this is due to the green construction and new construction technologies. Also noted for more accurate calculations a professional is needed to do an energy analysis and analysis of heat loss in the building. After doing this a system will be sized for these specific needs.

The design of the dormitory was based on a 207,400 square foot apartment/condominium complex in Westminster, Massachusetts. This building uses 6.2kwh/sq.ft./year by means of geothermal heat exchangers. If this number is applied to the new dormitory a total of 652668kwh/year would be used to heat and cool the building.

$$\frac{6.2kwh}{\frac{sqft}{year}} \times 105269sqft = \frac{652668kwh}{year}$$

This number is lower than the expected energy to be used in the new dormitory for heating and cooling. The system would have two wells with two 30-hp pumps providing approximately 1,500 gpm of water at 55^{0}F. It is believed that only one well will be in use at most times and the second well will only be needed for the hottest of summer days and the coldest of winter days. After the water is pumped into the building it will reach an Alpha Laval plate and frame heat exchanger. Alpha Laval plate and frame heat exchangers consists of a pack of thin metal plates with openings for the passage of the water. The plates are corrugated which means that each pair of adjacent plates in the heat exchanger forms a channel. Every second channel is open to the same fluid. Between each pair of plates there is a rubber gasket, which prevents the fluids from mixing and from leaking to the surroundings. When the water enters the plate and frame heat exchanger via the connections in the frame, it's directed through alternate channels by the gasket arrangement. The warm fluid flows through every other channel and the cold fluid through the channels in between. Heat is thus transferred from the warm fluid to the colder fluid via the dividing wall. The corrugations support the plates against differential pressure and create a turbulent flow in the channels. In turn, the turbulent flow provides high heat transfer efficiency, making the plate heat exchanger very compact (Valutech Inc.).

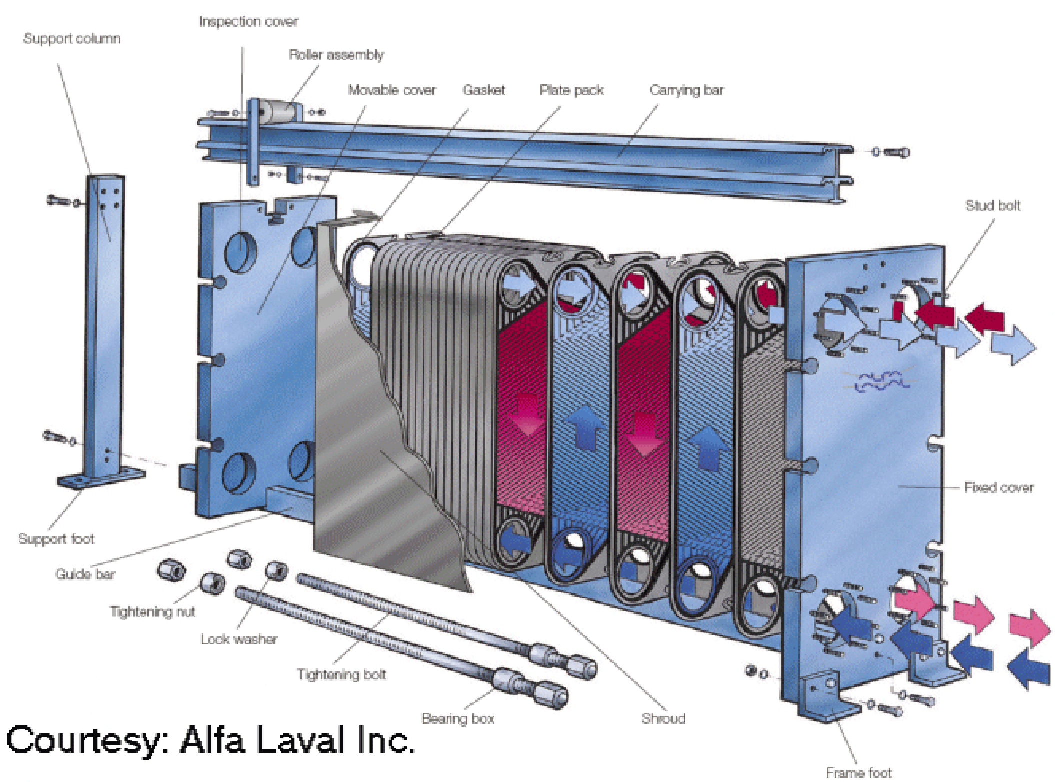


Figure 26: Plate Heat Exchanger

After the heat exchangers the water is pumped to three 200-ton water-to-water heat pumps. Each heat pump has two 100-ton compressors to further heat or cool the water. The water is then circulated through the dormitory by two 75 hp pumps. These pumps will supply a two-pipe system allowing for either heating or cooling. For heating water of 95^0F-110^0F is pumped to individual fan coil systems in each apartment. For cooling water of 52^0F-55^0F is circulated to the fan coil systems. In the months between winter and summer water circulates at about 60^0F. The temperature of each room can be controlled by wall mounted thermostats. The thermostats regulate valves in each fan coil unit thus allowing for individual control. After passing through the system the water would be discharged either back into the ground or into a manmade pond on the property (Bloomquist).

Geothermal heat pumps are a green way of heating and cooling a building. It is believed that heating and cooling of the new East Campus Dormitory can be achieved by a geothermal heating and cooling system. Not only is it green but it would require less electricity than the conventional HVAC system. Also with systems within the region of Worcester Polytechnic Institute it is clearly a real option that could have been applied.

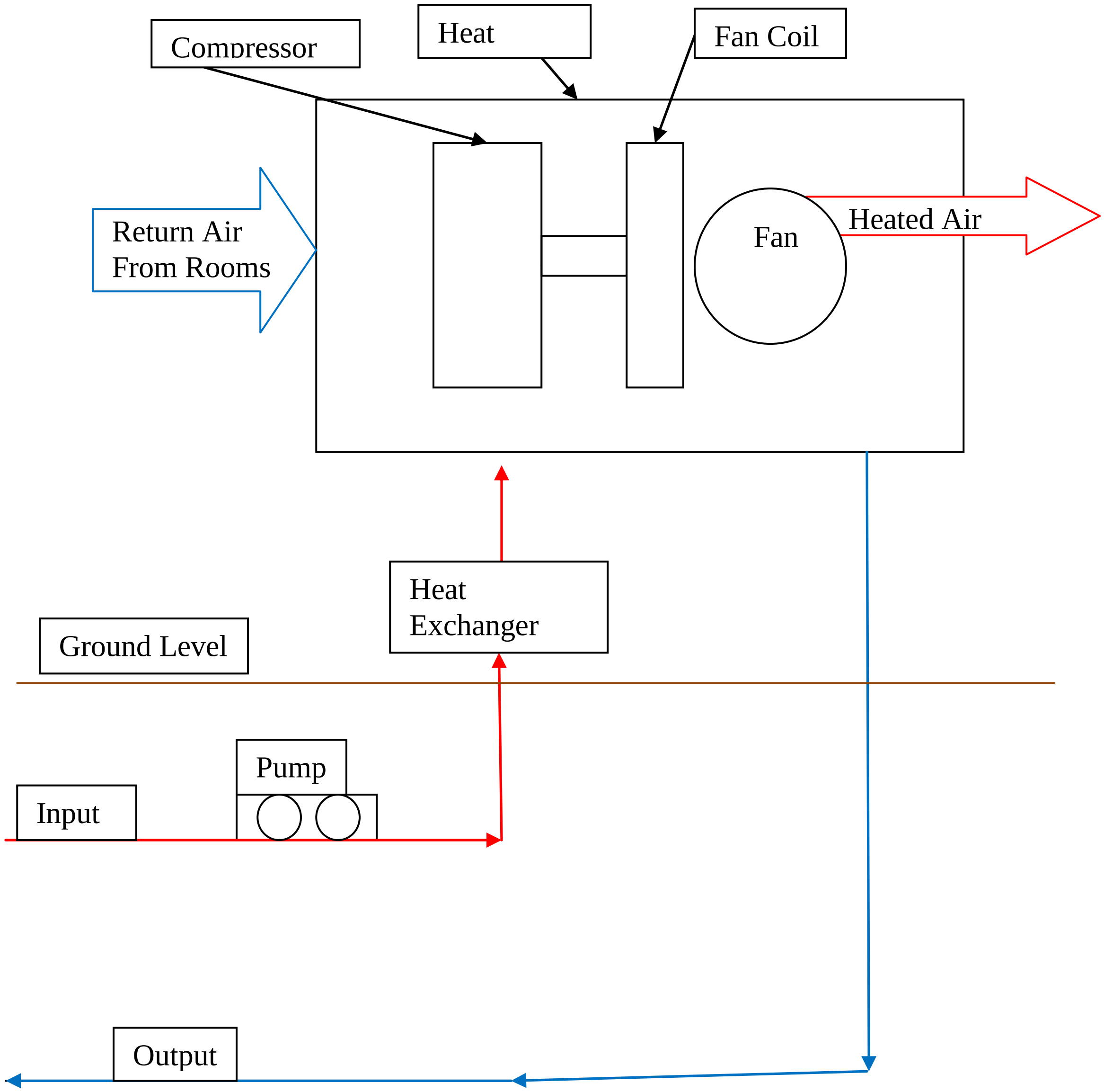


Figure 27: Heat Pump System for East Campus Dormitory

Wind Power

When analyzing means of generating on-site green electricity two different systems were presented, solar and wind. After analysis of each it was determined that a vertical axis wind turbine would be able to produce the most electricity and is the most efficient way of producing electricity. With current turbines working at an efficiency of 45-48% and the ability to place them on the roof of a large building the choice was clear. (TMA Wind)

Vertical axis wind turbines are designed with a vertical rotor shaft, a generator and gearbox which are placed at the bottom of the turbine, and a uniquely shaped rotor blade that is designed to harvest wind power no matter which direction the wind is blowing. This design allows for the placement of vertical axis wind turbines on the top of buildings. Vertical axis wind turbines are also able to produce electricity in non-laminar air flows. This means that any turbulence, microburst or wind shear conditions will have no negative effects on the turbine. Turbines are also designed to with stand winds of up to 110 mph and sustained winds of 70 mph for ten minutes before needing to be shut down (How Do Wind Turbines Work?).

When researching vertical axis wind turbines it was decided to use 5 kw systems from Terra Moya Aqua Inc (TMA). These systems measure 8 feet tall and can be placed in rows with a minimum separation of 8 feet in between turbines. The airfoils on the turbine are shaped like air plane wings and this design allows for a significant increase in efficiency. A typical vertical axis turbine can reach 39% efficiency where the TMA turbines achieve an efficiency of 45-48%. The wing shaped design increases the wind speed as it enters the throat of the turbine, allowing the turbine to work at lower speeds. Also using the wing shaped foils in conjunction with two flat air foils results in lift on the rotor and reduced pressure on the returning half as the rotor spins, this translates into lower drag and greater efficiency (TMA Wind). See appendix E for technical analysis of vertical axis wind turbines.

This wind turbine has been tested and produced 1100 kwh/month at an average wind speed of 13 mph. Wind speeds in the city of Worcester average 12.3 mph to 15.7 mph and the area of Worcester Polytechnic Institute averages 12.3 mph to 13.4 mph.

With this figure it was calculated that one 5kw system would produce 13200 kwh/year. With further calculations it was found that 196 5kw vertical axis wind turbines can be placed on the center, north and half of the south facing roofs. At 13200kwh/year the 196 turbines would be able to produce 2.58×10^6 kwh/year. This is more energy than the proposed building will be consuming.

$$\frac{1100kwh}{month} \times \frac{12month}{1year} = \frac{13200kwh}{year}$$

$$\frac{13200kwh}{year} \times 196 = 2.58 \times \frac{10^6 kwh}{year}$$

With these numbers it was determined that vertical axis wind turbines could have been included in the design of the East Campus Dormitory. Although adding 196 wind turbines will also add a significant amount of weight, with proper reinforcement and construction it is a feasible option.

Conclusions

The final analysis of sustainable energies for the East Campus Dormitory has yielded promising results. By utilizing LEED design criteria and a system of vertical axis wind turbines, passive solar water heating, and geothermal heating and cooling it was determined that enough energy could be produced onsite to power the building's reduced energy consumption. The LEED standards allow the building to conserve a great deal of energy when compared to a typical building of similar size. WPI's East Campus Dormitory will consume an estimated 32% less energy than standard buildings. This can be attributed to superior insulation techniques, modern technology that allows for more precise control of heating and cooling, and energy star rated appliances. This project analyzed current engineering practices and onsite energy generation technologies, and created a design that allows for an even further reduction in energy demand, if not eliminating it altogether.

The passive solar water heating system uses about 95% less energy than conventional gas fired methods. The energy recovered is recycled back to the incoming cold tap water and therefore raises the inlet temperature for the passive solar heating system. This design allows for the elimination of gas fired water heating, which eliminated carbon dioxide emissions and allows the water to be heated through clean energy produced on site, with the on demand electric water heaters providing backup heat when needed. This array will save an estimated 263,431 Kg of CO_2 per year from being released to the atmosphere (Apricus Solar).

The geothermal heat pump ventilation system allows for a reduction in the energy required for heating and cooling. This system uses the earth as a natural heat sink, based on the constant temperature underground. This system requires heat pumps which still require electricity, but still use less energy than conventional heating and cooling methods. By using electrical pumps and controls, the system can be powered by green onsite power instead of burning methane or using “dirty” electricity from the grid.

By installing multiple vertical axis wind turbines on the roof of the building, the entire electrical demand of the building could be met. Vertical axis wind turbines are over 40% efficient and are extremely reliable. These units are very quiet, and since they do not have to rotate to constantly face the wind, they eliminate many problems that are typically associated with horizontal axis turbines. Wind is a reliable source of energy as air currents are constantly shifting and therefore constantly turning the turbines.

Although wind is variable and unpredictable, over the course of a year the average production numbers could meet the entire demand of this application. If the building remains connected to the power grid, it can consume electricity like a standard building when energy production from the wind turbines is low. On windy days, the turbines should be able to produce the electricity needed by the building and possibly create a surplus, which could be sold back to the power grid. This allows the grid to be a type of storage system and over the course of a year the building should have a net outside electricity use of zero KWh. In theory, battery storage systems could be installed within the building to disconnect it from the power grid, however an analysis of the building’s performance would be necessary before cutting it off from the grid completely. Also, a battery storage system is extremely expensive and needs to be replaced every 8-10 years. Designs such as this can be implemented on any scale, and are possible with today’s technology as long as careful planning and designs are utilized. There is a new wave of green buildings being constructed across the world due to rising oil prices and environmental concerns, and so the buildings benefit both the economy and the environment.

Appendices

Appendix A: Biogas Production by Anaerobic Digestion

Digester Size:

Digester Size from McElvaney Associates Estimation:

$$\frac{(TS\ in\ waste)}{TS\%Batch} \times RenTime = Req.Vol$$

$$\frac{38.5kgTS}{0.1TS_{batch}} \times 30days = 11.55m^3$$

Digester Size from Rwandan Prison System:

$$\frac{150m^3 Digester\ \ Vol.}{1500 pers} = \frac{X\ m^3 Digester\ \ Vol.}{250 pers} \quad => \quad X = 25\ m^3$$

Averaged Volume for Dormitory Application:

$$\frac{25m^3 + 11.55m^3}{2} = 18.23m^3$$

Iowa Farm Estimate:

$$\left(\frac{gCOD\ fed}{day}\right)(CODreduction)\left(\frac{m^3CH_4}{gCOD}\right) = \frac{m^3CH_4}{m^3Digester\ Vol.}$$

To Find Loading Rate:

$$\frac{kgVS}{day} = \frac{\left(\frac{154\,g}{pers}\right)(250 pers)}{day} \times (.\frac{685VS}{TS}) \quad => \quad \frac{26.37kgVS}{18.3m^3} = \frac{1.44kgVS}{m^3} = \frac{1.44kgVS}{liter}$$

$$\Rightarrow \frac{1.44\text{kgVS}}{\text{liter}} \times \frac{1.25\text{COD}}{1\text{VS}} = \frac{1.8\text{kgCODfed}}{\text{day}}$$

From Original Equation:

$$\frac{1.8kgCODfed}{day} \times 0.40 \times \frac{0.375m^{3\ CH_4}}{kgCOD} = \frac{0.27m^3CH_4}{m^3Digester\ Vol.}$$

To Find Total Biogas (60% methane):

$\frac{0.27CH_4}{x} = \frac{60}{100}\%$ $x = \frac{0.45m^3CH_4}{m^3Digester\ \ Vol.}$

$$=> \frac{0.45m^3CH_4}{m^3Digester\ \ Vol.} \times 18.3m^3 Digester\ Vol. = \frac{8.24m^3CH_4}{day}$$

Klass Estimation:

$$\frac{26.37kgVS}{day} \times \frac{0.313m^3CH_4}{kgVS} = \frac{8.25m^3CH_4}{day}$$

To Find Total Biogas (60% methane):

$\frac{8.25m^3CH_4}{x} = \frac{60}{100}\%$ $x = \frac{13.75m^3}{day}$

McElvaney Associates Estimation:

$$(VS\ in\ Waste) \times (Digester\ Efficiency) \times (Gas\ Density@65\%CH_{4)} = Total\ Gas$$

$$\left(\frac{26.37kgVS}{day}\right) \times (0.8) \times \left(\frac{1m^3}{1.14kg}\right) = \frac{18.5m^3}{day}$$

Rwandan Prison System Estimation (Daily Output):

$\frac{5000persons}{250m^3biogas} = \frac{250persons}{X\ m^3biogas}$ => $X = 12.5\ m^3biogas$

$\frac{50m^3biogas}{100m^3digester\ \ vol.} = \frac{X\ m^3biogas}{18.3\ m^3digester\ \ vol.}$ $X = 9.15\ m^3biogas$

Annual Estimated Biogas Outputs:

$$\frac{12.55m^3biogas}{year} \times \frac{365days}{year} = \frac{4{,}580.75m^3biogas}{year}$$

$$\frac{4{,}580.75m^3biogas}{year} \times \frac{35.315ft^3}{1m^3} = \frac{161{,}800ft^3biogas}{year}$$

$$\frac{161{,}800ft^3biogas}{year} \times \frac{600Btus}{ft^3} = \frac{97{,}080{,}000Btus}{year}$$

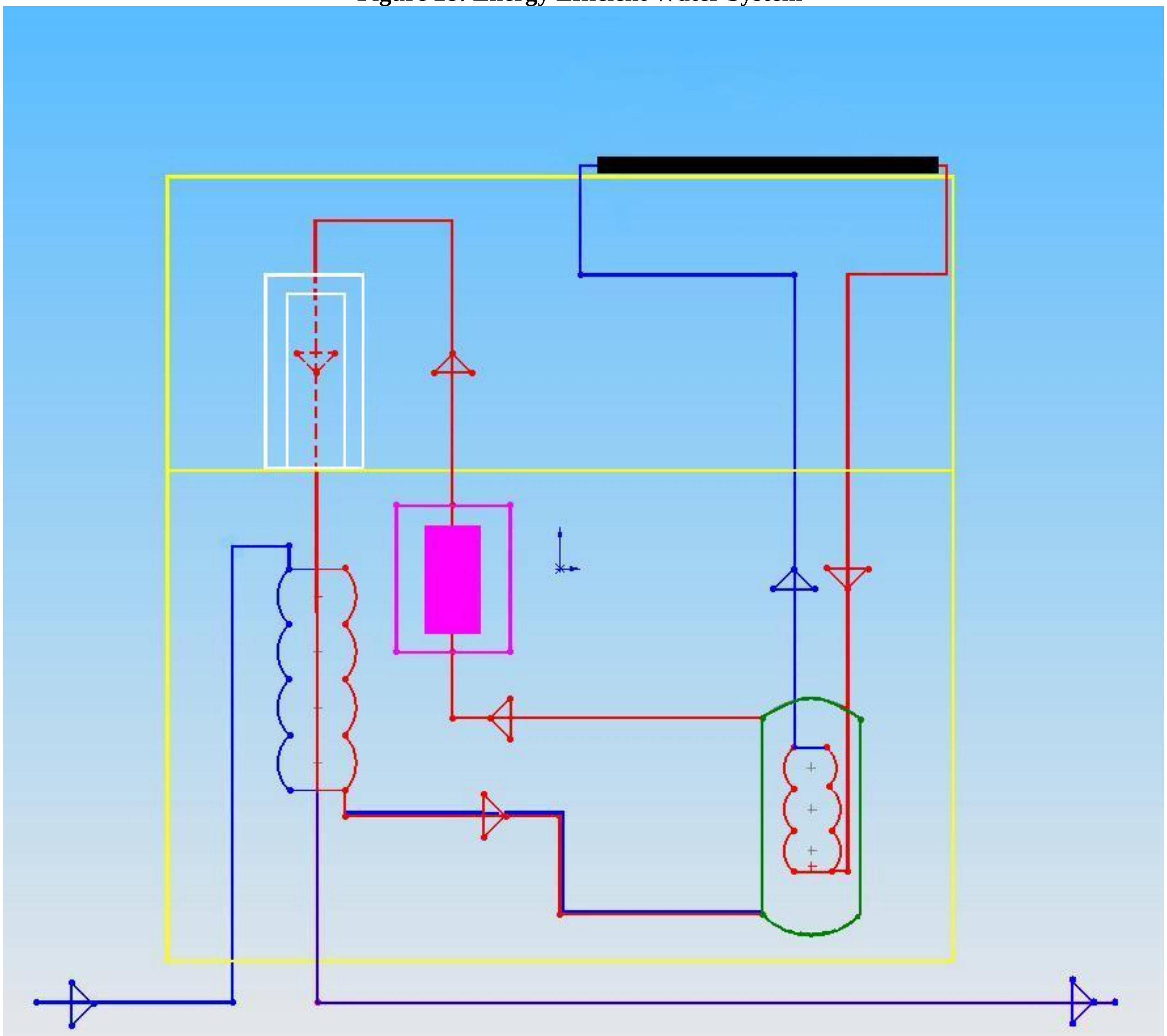
$$\frac{97{,}080{,}000Btus}{year} \times \frac{1therm}{100{,}000Btus} = \frac{971therms}{year}$$

Annual Biogas Output compared to Dormitory Annual Natural Gas needs:

$$\frac{971 therms}{46{,}646 therms} = 2.1\%\ Dormitory\ Needs$$

Appendix B: Solar Water Heating with Drain Water Heat Recovery System

Figure 28: Energy Efficient Water System



This diagram was constructed using SolidWorks and then color coded and highlighted with Paint. On the left the cold tap water is pulled into the building from the water company. The water is immediately run though the heat recovery system that wraps around the shower drain pipes as shown in Figure 30 (Clean Break). If the shower is inactive the water simply passes through the recovery system and emerges at the same temperature, however if the shower is active the incoming water will be heated to approximately 80.5 °F and enter the bottom of the solar heating tank (shown as the green cylinder). This tank contains coils that contain a glycol solution that will not freeze in cold conditions. The cool solution is pumped to the roof and pass though each of the tubes (30 tube systems connected in series for a total of 150 tubes per solar tank). The cool solution is run though capillaries that enter each evacuated tube, travel to the end, make a u-turn, and return to the manifold to be channeled to the adjacent tube as shown in Figure 31 (Apricus Solar). The hot liquid returns to the bottom of the tank where it loops around several times before making it back to the top, and releasing most of its thermal energy along the way. Whenever water is needed it can be pulled from the tank and sent to the showers at 115 °F. If for some reason the standard heating is not enough to heat the water in a timely manner due to increased loads or extended dark cloudy days, the electric on-demand water heater (purple box in line after the solar heating tank) will be activated and provide the water with the extra energy it needs before entering the shower for use. After the hot water flows through the shower head and begins to exit the building, it will pass through the heat recovery system, and release over 70% of its energy to the cold water entering the building. The water then exits the building and begins its travel to the water treatment plant. Once the system is in use the water incoming to the solar heating tank will be much warmer and further decrease the load on the system. This design actually performs better the more it is used, which is the opposite of most other heating and cooling applications. In addition, an illustration in Figure 32 shows the proposed roof layout of the building, where the green section would be devoted to vertical axis wind turbines, and the black section on the south roof would be devoted to the evacuated solar tubes.

Figure 29: Drain Water Heat Recovery System

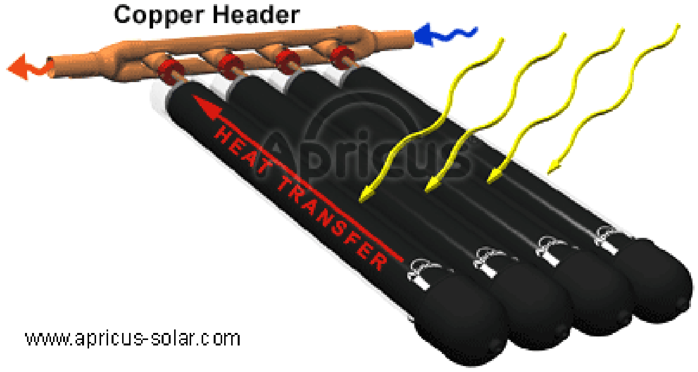


Figure 30: Evacuated Tube Illustration

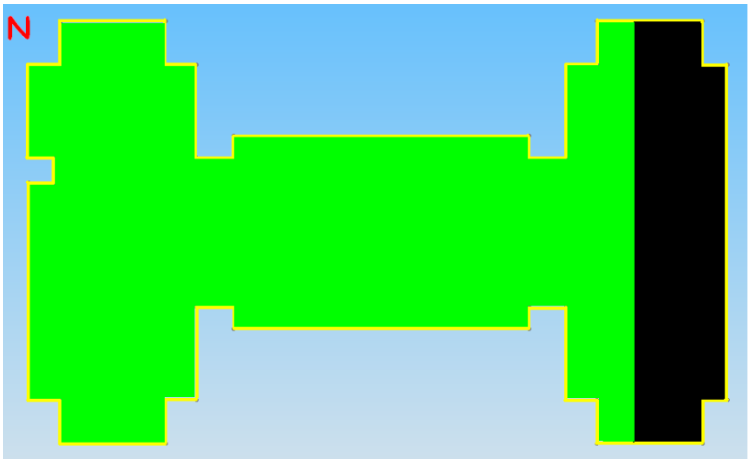


Figure 31: Proposed Roof Layout

Calculations:

Water Demand Calculations:

For a single shower system, the calculations are as follows:

$$\frac{232\ students}{4\ floors} = \mathbf{58}\ \frac{students}{floor} = \mathbf{11.6}\frac{students}{shower} = \mathbf{17.4}\ \frac{uses}{\frac{shower}{day}}$$

The actual amount of water that must be heated to 115 degrees:

$$25\ \frac{gallons}{shower} = \mathbf{18.33}\ \frac{gallons\ of\ hot\ water}{shower}$$

Each shower will consume:

$$\left(18.33\ \frac{gallons\ of\ hot\ water}{shower}\right)(17.4\ \frac{showers}{day}) = \mathbf{319}\frac{gallons\ of\ hot\ water}{day}$$

By assuming the drain water recovery system recovers 70% of the temperature of the 115 °F exiting water, and the average incoming tap water is 59 °F, the temperature of the water exiting the recovery system is 80.5 °F. To get it back to 115 °F, the solar system needs to add 34.5 °F.

Solar Thermal Production:

The average solar insolation of Worcester is 3.58 $KWh/m^2/day$. By using Apricus's online estimation tool, the number of evacuated solar tubes needed to raise 319 gallons of water by 34.5 degrees is 134 tubes. The systems come in modules of 20, 22, 25, and 30. By connecting five 30 tube modules in series a total of 150 tubes per system is achieved.

Amount of energy needed per shower:

$$Q = cm\Delta T$$

$$Q_{319\ gallons} = \left(4.19\ \frac{J}{gram°C}\right)\left(319 * 3.7853\frac{Kg}{gallon}\right)\left(34.5 * \frac{5}{9}\right) = \mathbf{98379}\frac{kJ}{day}$$

$$= \mathbf{27.33} \frac{KWh}{day}$$

A 150 Apricus evacuated tube array has an area of 13.24m2. Also, the lowest efficiency achieved is 62%. This value is used to compensate for variations in solar insolation throughout the year. This means on a somewhat overcast day the array will produce:

$$\left(3.58 \frac{KWh}{\frac{m^2}{day}}\right)(13.24m^2) = \left(47.4 \frac{KWh}{day}\right)(.62) = \mathbf{29.4} \frac{Kwh}{day}$$

The total roof area required is:

$$\left(\frac{142.5\ ft^2}{array}\right)(24\ arrays) = \mathbf{3420}\ ft^2$$

It is worth noting that on an average day the system is about 70-75% efficient, and on very sunny days it nears 90% efficient. This system clearly meets the needs of WPI's new residence hall. By installing 6 of these systems per floor (5 for showers and 1 for faucets) the energy produced exceeds the amount of energy required without any electrical thermal heating. Each system uses a 40 watt motor to pump the glycol solution to the roof, which totals about 1Kw.

Annual energy consumption:

$$(1Kw)\left(6\ \frac{hours}{day}\right)\left(30\ \frac{days}{month}\right)\left(12 \frac{months}{year}\right) = \mathbf{2160}\ \frac{KWh}{year}$$

If these pumps are powered by a single wind turbine which produces 158,400KWh/year, the entire annual demand for the water heating system is met with about 5 days of wind power production from a single turbine. If the water for the building is heated by standard natural gas water heating it would consume the following amount of energy:

$$Q = cm\Delta T$$

$$Q = \left(4.19\ \frac{J}{gram℃}\right)\left(8260 * 3.7853\frac{Kg}{gallon}\right)\left((115-59)*\frac{5}{9}\right) = 4078239\ \frac{kJ}{day} = \mathbf{1133}\frac{KWh}{day}$$

This system must heat the tap water from 59 °F all the way up to 115 °F. Also, without a heat recovery system it must always heat the tap water by that margin. This number also assumes 100% efficiency, which is far from possible. A typical energy efficient heater is 60% efficient, and adjusted energy consumption is 1587KWh/Day.

Annual energy consumption is:

$$\left(1587\frac{KWh}{day}\right)\left(30\ \frac{days}{month}\right)\left(12\frac{months}{year}\right) = \mathbf{571,320}\ \frac{KWh}{year}$$

This equates to the solar thermal with heat recovery using 99.6% less energy per year. Even if the worst case scenario occurred and the electrical on-demand water heaters were used more than projected due to bad weather, an energy savings of at least 90-95% a year can be expected. This makes sense when heat recovery systems boast the fact that they can save over 70% of the thermal energy required for heating, and solar thermal systems advertise savings up to 80% annually. By combining the 2 systems into one the energy savings is astounding. This system is clearly applicable to WPI's new dorm building and any building for that matter. The area required is about 1/5 the total roof area and the system is not a very complicated installation. This water heating system is a testament to innovative green engineering and should be implemented into buildings in the near future.

Appendix C: Doyle Conservation Center Write up

Energy Conservation and Production:

- The efficient design and insulation allows the building to use 40 percent less fuel than other buildings of a similar size.
- The building has achieved 55% efficiency, which means it is 55% more efficient than governing codes.
- The ERV captures energy for reuse by utilizing the heat wheel to transfer energy from the exhaust air to the fresh incoming air.
- 20-25% of the buildings total power is produced on the roof via photovoltaic power. The array contains 144 panels with a total of 2,000 square feet.
- "Smart lights" automatically adjust to the lighting needs of the building.
- Windows open to allow for good ventilation.
- Geothermal heating and cooling control the temperature of the building without using fossil fuels, and the heating management system helps to regulate the air temperature with the lowest energy costs.
- Triple glazed windows limit the amount of energy that escapes the building.
- Roman columns utilized on either side of the building to promote ventilation.

Water Conservation:

- The waterless composting toilet system uses 80% less water than a normal toilet, consuming only 3 ounces of water per flush.
- Rainwater from the roof is collected and returned to the land through an irrigation system to reduce water consumption of building.
- Indigenous plant life is used on site to reduce the amount of maintenance required in an effort to save energy.

Environmental Friendliness and Indoor Quality:

- On-site recycling center provides repository for all paper products and glass and metal containers.
- Over 50% of the construction materials were recycled.
- Recycled and renewable materials are used all around the building.
- Bamboo and cork flooring, desks and shelving made of sunflower seed byproducts, Werzalit siding made from a byproduct of hardwood timber harvesting, carpeting made from recycled fibers.
- Fabric on cubicle walls made of recycled fibers, stonework made from stone found on site, mulch form stumps used in landscaping.
- AVONITE sink counters are a "zero waste" product. The powder byproduct is sent to other companies to reuse in their products. Through this the manufacturer prevents

300,000 pounds of waste from entering landfills each year. AVONITE also saves 100,000 gallons of water and destroys 95% of VOC's through this recycling process.

- Low VOC paint used to minimize "off gassing."

Appendix D: East Campus Dormitory Write-up:

Specifications:

- Silver/Gold Certified.
- 232 beds on 4 floors.
- Single, double, and 4 bedroom suites, plus Resident Advisor suites.
- 16 apartments per floor.
- Project rooms, gaming rooms, tech suite.

Energy Conservation and Production:

- Will be using energy star rated appliances to conserve energy.
- Windows are equipped with sensors to detect when they are open or closed. When open, the heating or cooling to that room will shut off to conserve energy.
- Large windows allow for daylight to illuminate building thereby reducing the lighting requirement.
- Spray insulation on exterior walls to help insulate building and drive down energy cost.
- By utilizing a "cool roof" which reflects heat more efficiently; cooling loads will be directly reduced during hot days.

Water Conservation:

- Utilizing water efficient landscaping to reduce water consumption for agriculture by 50%
- No irrigation will be used for landscaping.
- Indigenous plants will be used so they don't require any water.
- Storm water runoff is directed to the local agriculture instead of into storm drains, therefore reducing the amount of waste water.

Environmental Friendliness and Indoor Quality:

- Low VOC paint used to minimize "off gassing."
- Low-emitting adhesives and sealants, paints and coatings, carpet systems, and composite wood and agrifiber products.
- On-site recycling center provides repository for all paper products and glass and metal containers.
- Metal dumpster, wood dumpster, gypsum dumpster, and 2 general dumpsters on site during construction for recycling and reuse.
- 20% of extracted materials and processed and manufactured within 500 miles.
- Easy access to public transportation and bicycle storage and changing rooms.
- Outdoor air delivery monitoring improves the indoor air quality by bringing in fresh air.

Expected energy consumption of building:

East Dorm	Proposed Design		Baseline Design		Percent Savings	
	Energy Use	Cost	Energy Use	Cost	Energy	Cost
Electricity	2,034,059 kWh	$284,768	2,567,847 kWh	$359,499	20.80%	20.80%
Natural Gas	42,646 therms	$55,439	77,603 therms	$100,884	45%	45%
Total:	11,205 (MBtu/year)	$340,207	16,522 (MBtu/year)	$460,383	32.20%	26.10%

LEED-NC

LEED-NC Version 2.2 Registered Project Checklist

New Residence Hall, Worcester Polytechnic Institute, Worcester MA
DD Update 4.2.07

Sustainable Sites

Yes	?	No				Responsibility
10	2			Sustainable Sites		
Y			Prereq 1	Construction Activity Pollution Prevention		CE
1			Credit 1	Site Selection		CE
1			Credit 2	Development Density & Community Connectivity		CE
			Credit 3	Brownfield Redevelopment		
1			Credit 4.1	Alternative Transportation,	Public Transportation Access	CD
1			Credit 4.2	Alternative Transportation,	Bicycle Storage & Changing Rooms	CD
	1		Credit 4.3	Alternative Transportation,	Low-Emitting and Fuel-Efficient Vehicles	CD
1			Credit 4.4	Alternative Transportation,	Parking Capacity	CD
			Credit 5.1	Site Development,	Protect of Restore Habitat	
1			Credit 5.2	Site Development,	Maximize Open Space	CD
	1		Credit 6.1	Stormwater Design,	Quantity Control	CE
1			Credit 6.2	Stormwater Design,	Quality Control	CE
1			Credit 7.1	Heat Island Effect,	Non-Roof	CD
1			Credit 7.2	Heat Island Effect,	Roof	CD
1			Credit 8	Light Pollution Reduction		MEP-CD

Water Efficiency

Yes	?	No				Responsibility
4				Water Efficiency		
1			Credit 1.1	Water Efficient Landscaping,	Reduce by 50%	BSI
1			Credit 1.2	Water Efficient Landscaping,	No Potable Use or No Irrigation	BSI
			Credit 2	Innovative Wastewater Technologies		
1			Credit 3.1	Water Use Reduction,	20% Reduction	MEP-CD
1			Credit 3.2	Water Use Reduction,	30% Reduction	MEP-CD

Energy & Atmosphere

Yes	?	No			Responsibility
6	2			Energy & Atmosphere	
Y			Prereq 1	Fundamental Commissioning of the Building Energy Systems	Cx- RDK
Y			Prereq 2	Minimum Energy Performance	MEP-CD
Y			Prereq 3	Fundamental Refrigerant Management	MEP-CD
4	1		Credit 1	Optimize Energy Performance	MEP-CD
			Credit 2	On-Site Renewable Energy	
1			Credit 3	Enhanced Commissioning	Cx-RDK
1			Credit 4	Enhanced Refrigerant Management	MEP-CD
			Credit 5	Measurement & Verification	
	1		Credit 6	Green Power	RMEC

RMEC 3.15.07

Yes	?	No		
6	1		**Materials & Resources**	

Yes	?	No			
Y			Prereq 1	**Storage & Collection of Recyclables**	CD
			Credit 1.1	**Building Reuse**, Maintain 75% of Existing Walls, Floors & Roof	
			Credit 1.2	**Building Reuse**, Maintain 100% of Existing Walls, Floors & Roof	
			Credit 1.3	**Building Reuse**, Maintain 50% of Interior Non-Structural Elements	
1			Credit 2.1	**Construction Waste Management**, Divert 50% from Disposal	GBC
1			Credit 2.2	**Construction Waste Management**, Divert 75% from Disposal	GBC
			Credit 3.1	**Materials Reuse**, 5%	
			Credit 3.2	**Materials Reuse**,10%	
1			Credit 4.1	**Recycled Content**, 10% (post-consumer + ½ pre-consumer)	GBC
1			Credit 4.2	**Recycled Content**, 20% (post-consumer + ½ pre-consumer)	GBC
1			Credit 5.1	**Regional Materials**, 10% Extracted, Processed & Manufactured Regic	GBC
	1		Credit 5.2	**Regional Materials**, 20% Extracted, Processed & Manufactured Regic	GBC
			Credit 6	**Rapidly Renewable Materials**	
1			Credit 7	**Certified Wood**	GBC

Yes	?	No		
11			**Indoor Environmental Quality**	

Yes	?	No			
Y			Prereq 1	**Minimum IAQ Performance**	MEP-CD
Y			Prereq 2	**Environmental Tobacco Smoke** (ETS) **Control**	WPI
1			Credit 1	**Outdoor Air Delivery Monitoring**	MEP-CD
			Credit 2	**Increased Ventilation**	
1			Credit 3.1	**Construction IAQ Management Plan**, During Construction	GBC
1			Credit 3.2	**Construction IAQ Management Plan**, Before Occupancy	GBC
1			Credit 4.1	**Low-Emitting Materials**, Adhesives & Sealants	GBC
1			Credit 4.2	**Low-Emitting Materials**, Paints & Coatings	GBC
1			Credit 4.3	**Low-Emitting Materials**, Carpet Systems	GBC
1			Credit 4.4	**Low-Emitting Materials**, Composite Wood & Agrifiber Products	GBC
1			Credit 5	**Indoor Chemical & Pollutant Source Control**	MEP-CD
1			Credit 6.1	**Controllability of Systems**, Lighting	MEP-CD
			Credit 6.2	**Controllability of Systems**, Thermal Comfort	
			Credit 7.1	**Thermal Comfort**, Design	
			Credit 7.2	**Thermal Comfort**, Verification	
1			Credit 8.1	**Daylight & Views**, Daylight 75% of Spaces	CD
1			Credit 8.2	**Daylight & Views**, Views for 90% of Spaces	CD

Yes	?	No		
2	3		**Innovation & Design Process**	

Yes	?	No			
1			Credit 1.1	**Innovation in Design**: Green Building Education (signage & ed. website)	CD
	1		Credit 1.2	**Innovation in Design**: Green Housekeeping (6 month supply to students)	CD
	1		Credit 1.3	**Innovation in Design**: Exemplary Perforamce for MRc2 (95%) -recycle	GBC
	1		Credit 1.4	**Innovation in Design**: Exemplary Perforamce for MRc4 (30%) —30%	GBC
1			Credit 2	**LEED® Accredited Professional**	RMEC

Yes	?	No		
39	8		**Project Totals** (pre-certification estimates)	

Certified 26-32 points **Silver** 33-38 points **Gold** 39-51 points **Platinum** 52-69 points

RMEC 3.15.07

Appendix E Technical Analysis of Wind Power

Taylor, Ronald J. (1169 Long Valley Dr., Cheyenne, WY, 82001) 2000 Wind turbine United States 6015258 http://www.freepatentsonline.com/6015258.html

What is claimed is:

1. A wind-actuated electric power alternator, comprising: an impeller enclosure having a generally triangular cross-sectional configuration; an impeller rotatably mounted in said impeller enclosure; and a alternator coupled to said impeller.

2. The wind-powered electric power alternator of claim 1 wherein said impeller enclosure has a generally equilateral triangular configuration.

3. The wind-powered electric power alternator of claim 1 further comprising a base and wherein said impeller enclosure is carried by said base.

4. The wind-powered electric power alternator of claim 1 wherein said impeller comprises an impeller shaft coupled to said alternator, an impeller body carried by said impeller shaft and a plurality of impeller blades and a base plate carried by said impeller body.

5. The wind-powered electric power alternator of claim 4 wherein said plurality of impeller blades each has a generally curved cross-sectional configuration.

6. The wind-powered electric power alternator of claim 4 further comprising a pulley wheel

carried by said impeller shaft, a alternator drive wheel carried by said alternator and a alternator drive belt coupling said pulley wheel to said alternator drive wheel.

7. The wind-powered electric power alternator of claim 4 further comprising a flywheel carried by said impeller shaft, disk brakes engaging said base plate and a brake engaging said flywheel for selectively grabbing said flywheel against said disk brakes.

8. The wind-powered electric power alternator of claim 4 further comprising an impeller mount frame provided in said impeller enclosure and wherein said impeller shaft is mounted in said impeller mount frame.

9. A wind-actuated electric power alternator, comprising: an impeller enclosure having a plurality of enclosure panels defining generally triangular cross-sectional configuration; a panel opening provided in each of said plurality of enclosure panels; an impeller rotatably mounted in said impeller enclosure; and a alternator adapted to be coupled to said impeller when said impeller reaches a predetermined rotational speed.

10. The wind-actuated electric power alternator of claim 9 wherein said impeller enclosure has a generally equilateral triangular configuration.

11. The wind-powered electric power alternator of claim 1 further comprising a base having a generally triangular cross-sectional configuration and wherein said impeller enclosure is carried by said base.

12. The wind-powered electric power alternator of claim 9 wherein said impeller comprises an impeller shaft coupled to said alternator, a generally cylindrical impeller body carried by said impeller shaft and a plurality of elongated impeller blades carried by said impeller body.

13. The wind-powered electric power alternator of claim 12 wherein said plurality of impeller blades each has a generally curved cross-sectional configuration.

14. The wind-powered electric power alternator of claim 12 further comprising a pulley wheel carried by said impeller shaft, a alternator drive wheel carried by said alternator and a alternator drive belt coupling said pulley wheel to said alternator drive wheel.

15. The wind-powered electric power alternator of claim 12 further comprising a flywheel carried by said impeller shaft and a brake engaging said flywheel for selectively pushing said flywheel against said impeller body.

16. The wind-powered electric power alternator of claim 12 further comprising an impeller mount frame provided in said impeller enclosure and wherein said impeller shaft is rotatably mounted in said impeller mount frame.

17. A wind-actuated electric power alternator, comprising: an impeller enclosure having a plurality of enclosure panels defining generally triangular cross-sectional configuration; a panel opening provided in each of said plurality of enclosure panels; a plurality of louvers provided in

said panel opening; an impeller rotatably mounted in said impeller enclosure; and a alternator adapted to be coupled to said impeller when said impeller reaches a predetermined rotational speed.

18. The wind-actuated electric power alternator of claim 17 wherein said impeller comprises an impeller shaft coupled to said alternator; a generally elongated, cylindrical impeller body carried by said impeller shaft; and a plurality of elongated impeller blades carried by said impeller body.

19. The wind-actuated electric power alternator of claim 18 wherein said plurality of impeller blades each has a generally curved cross-sectional configuration.

20. The wind-actuated electric power alternator of claim 18 further comprising a flywheel carried by said impeller shaft and a brake engaging said flywheel for selectively pushing said flywheel against said impeller body.

Description

FIELD OF THE INVENTION

The present invention relates to apparatus for generating energy. More particularly, the present invention relates to a wind-actuated electric power alternator which is environmentally-friendly and efficient.

BACKGROUND OF THE INVENTION

Various types of wind-actuated power alternators are known in the art for converting wind power into electrical power. However, many conventional wind-actuated power alternators have a complex design which renders the alternators inefficient. Furthermore, many conventional wind-actuated power alternators have unenclosed rotating blades which can be harmful to wildlife. Therefore, a wind-actuated electrical power alternator is needed which is efficient, environmentally-friendly and does not pose a danger to wildlife.

SUMMARY OF THE INVENTION

The present invention is generally directed to a wind-actuated electric power alternator which is efficient, environmentally-friendly and does not pose a danger to wildlife. The wind-actuated electric power alternator includes an impeller enclosure having a generally triangular cross-sectional configuration. An impeller is rotatably mounted in the impeller enclosure. A alternator is coupled to the impeller for generating electricity responsive to wind-blown rotation of the impeller in the impeller enclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 is a perspective view of an illustrative embodiment of the wind-actuated electric power alternator according to the present invention;

FIG. 2 is a cross-sectional view of the wind-actuated electric power alternator, illustrating an impeller and electric alternator provided in an enclosure of the alternator; and

FIG. 3 is a side view of the impeller, illustrating a typical belt arrangement for connecting the impeller to the electrical alternator.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the drawings, an illustrative embodiment of the wind-actuated electric power alternator according to the present invention is generally indicated by reference numeral 1. The wind-actuated electric power alternator 1 typically includes a base 2 which may have a generally triangular cross-sectional configuration. The base 2 includes multiple, generally planar base sides 3 which are connected at acute angles with respect to each other at multiple base corners 3a. Preferably, the base 2 has the configuration of an equilateral triangle, with the base sides 3 having substantially the same length. The base sides 3 together define a base interior 5, as shown in FIG. 3. A base flange 4 may be provided along the bottom edge of the base 2 to facilitate mounting the base 2 to a flat support surface (not shown).

An impeller enclosure 8 is provided on the base 2. The impeller enclosure 8 has a cross-sectional configuration which generally matches that of the base 2 and includes multiple enclosure panels 9 which are connected to each other at acute angles with respect to each other at multiple enclosure corners 9a. An enclosure top 12 is provided on the upper ends of the enclosure panels 9. The enclosure panels 9 and enclosure top 12 together define an enclosure interior 13, as shown in FIG. 2. The enclosure interior 13 of the impeller enclosure 8 communicates with the base interior 5 of the base 2.

A panel opening 10 extends through each enclosure panel 9 and communicates with the enclosure interior 13. Preferably, each panel opening 10 has a generally elongated, rectangular configuration. Multiple louvers 11 typically span each panel opening 10 in a generally vertical configuration. Preferably, the louvers 11 are adjustably mounted in each panel opening 10 in such a manner that the louvers 11 can be selectively angled between an open configuration, as shown in FIG. 2, and a closed position (not shown). The louvers 11 are adjustable independently with respect to each other.

An impeller mount frame 30 is provided in the base interior 5 of the base 2. A bearing seat 32 is provided in the upper surface of the impeller mount frame 30, and a roller bearing 24 is seated in the bearing seat 32. A shaft opening 31 extends through the roller bearing 24 and the impeller mount frame 30. An impeller shaft 22 extends through the shaft opening 31. Accordingly, the impeller shaft 22 freely rotates in the roller bearing 24 and extends both above and beneath the impeller mount frame 30. An impeller 16 is provided on the impeller shaft 22, above the impeller mount frame 30, and is oriented in a generally vertical configuration in the enclosure interior 13.

The impeller 16 typically includes a generally elongated, cylindrical impeller body 17. Multiple impeller blades 18 extend outwardly from the exterior surface of the impeller body 17, in spaced-apart relationship to each other around the circumference of the impeller body 17. The impeller blades 18 may be elongated and traverse substantially the entire vertical extent or length of the impeller body 17, or alternatively, may traverse a portion of the vertical extent or length of the impeller body 17. Preferably, the impeller blades 18 have a generally curved cross-sectional configuration, as shown in FIG. 2, and extend outwardly in a generally arcuate path from the impeller body 17, into the enclosure interior 13.

The impeller 16 may be mounted on the impeller shaft 22 using any suitable technique which is known by those skilled in the art. For example, the impeller body 17 may be attached to a bearing 23 which is mounted on the impeller shaft 22. Preferably, a flywheel 26 is mounted on the shaft 22 beneath the impeller 16, and the shaft 22 normally rotates freely with the flywheel 26. A spacer 25 may be provided between the flywheel 26 and the lower end of the impeller body 17 and also between the flywheel 26 and the roller bearing 24. A brake 27, which may be hydraulic, for example, is provided on the impeller mount frame 30 and engages the flywheel 26. The brake 27 is actuated by a typically manual brake control mechanism (not shown). Accordingly, through actuation of the brake control mechanism (not shown), the brake 27 grabs the flywheel 26 against disk brakes 41 which are bolted or otherwise attached to a base plate 40 provided on the impeller body 17. Thus, the brake 27 transfers energy from the flywheel 26 to the base plate 40 to selectively prevent rotation of the impeller 16 and the impeller shaft 22. The flywheel 26 and brake 27 can be selectively disengaged from the disk brakes 41 and base plate 40, through release of the brake control mechanism, to again facilitate rotation of the impeller 16 and the impeller shaft 22.

A pulley wheel 34 is mounted on the impeller shaft 22, beneath the impeller mount frame 30. The pulley wheel 34 may be secured on the impeller shaft 22 using a washer 38 and securing nut 39, for example. An electric alternator 36, having a alternator drive wheel 37, is mounted in the base interior 5, beneath the impeller mount frame 30. A alternator drive belt 35 connects the pulley wheel 34 to the alternator drive wheel 37 of the alternator 36. Accordingly, the alternator drive belt 35 is operable to transmit rotation from the impeller shaft 22 to the alternator drive wheel 37 of the alternator 36, thereby driving the alternator 36. A second pulley wheel 34a may be likewise provided on the impeller shaft 22, above or below the pulley wheel 34, and connected to a second alternator (not shown) in like manner. An instrument panel (not shown) may be provided on the exterior surface of the base 2 or impeller enclosure 8, for example, and may include, for example, an RPM gauge which indicates the rotational speed of the impeller shaft 22 as well as at least one voltmeter which indicates the voltage of each alternator 36.

In typical operation of the wind-actuated electric power alternator 1, the louvers 11 on the enclosure panels 9 of the impeller enclosure 8 are positioned in an open configuration to facilitate the flow of wind through one set of louvers 11, through the enclosure interior 13 and out another set of louvers 11, as shown in FIG. 2. The wind blows against the typically curved impeller blades 18, thus causing the impeller 16 to rotate in the clockwise direction as indicated by the arrows in FIG. 2. The impeller 16 transmits rotation to the impeller shaft 22 through the bearing 23. The impeller shaft 22, in turn, transmits rotation to the pulley wheel 34, which rotates the alternator drive wheel 37 of the alternator 36 through the alternator drive belt 35. The alternator 36 generates electrical power, which may be stored in a suitable electrical storage device (not shown) for later use or may be used to power electronic components of any machine or device (not shown) simultaneously. The pulley wheel 34 may be adapted to rotate the alternator drive wheel 37 through the alternator drive belt 35 only when the impeller shaft 22 reaches a threshold rotational speed, such as, for example, 5 rpm, or when the wind speed reaches a predetermined magnitude, such as, for example, 10 mph.

When operation of the wind-actuated electric power alternator 1 is not desired, rotation of the impeller 16 and impeller shaft 22 in the enclosure interior 13 can be stopped by actuation of the brake 27 and flywheel 26, as was noted hereinabove. Additionally or alternatively, the louvers 11 on the enclosure panels 9 can be closed to prevent the flow of wind into the enclosure interior 13. Additionally or alternatively, the pulley wheel 34 may be adapted to rotatably disengage the alternator drive wheel 37 when the rotational speed of the impeller shaft 22 drops below the threshold rotational speed or when the wind speed drops below the predetermined magnitude.

In an illustrative method of assembly of the wind-actuated electric alternator 1, the base plate assembly is constructed. The impeller mount frame 30 is installed typically on a concrete surface (not shown). The roller bearing 24 is seated in the bearing seat 32, the impeller shaft 22 is inserted through the roller bearing 24 and the alternator or alternators 36 is/are connected to the impeller shaft 22. The impeller shaft 22 may be adapted to rotatably engage the alternator 36 when the rotational speed of the impeller shaft 22 reaches a predetermined magnitude, such as, for example, 5 RPM, or when the wind speed reaches a predetermined value, such as, for example, 10 mph. Next, straps (not shown) are attached to the impeller mount frame 30 and extended upwardly. The brake 27 is also installed on the impeller mount frame 30. Next, the flywheel 26, impeller 16 and disk brakes 41 are installed on the impeller shaft 22. The straps (not shown) are attached to the impeller mount frame typically using hex bolts. The base 2 and impeller enclosure 8 are then installed around the impeller mount frame 30 and impeller 16, and the louvers 11 are provided in the impeller enclosure 8.

While the preferred embodiments of the invention have been described above, it will be recognized and understood that various modifications can be made in the invention and the appended claims are intended to cover all such modifications which may fall within the spirit and scope of the invention.

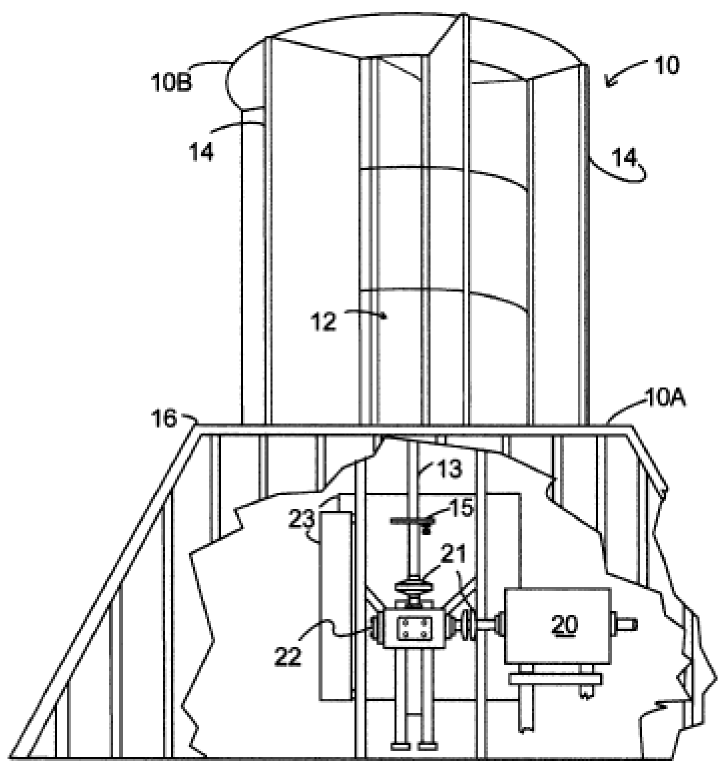


FIGURE 1

US006015258A

United States Patent [19]

Taylor

[11] **Patent Number: 6,015,258**

[45] **Date of Patent: Jan. 18, 2000**

[54] **WIND TURBINE**

[76] Inventor: **Ronald J. Taylor**, 1169 Long Valley Dr., Cheyenne, Wyo. 82001

[21] Appl. No.: **09/061,508**

[22] Filed: **Apr. 17, 1998**

[51] **Int. Cl.**[7] **F03D 3/04**; F03D 7/00

[52] **U.S. Cl.** .... **415/4.4**; 415/2.1; 415/4.2; 415/121.2; 415/208.3; 415/211.1; 415/907; 416/132 R; 416/196 A; 416/244 D; 416/DIG. 6

[58] **Field of Search** .... 415/2.1, 4.2, 4.4, 415/121.2, 186, 208.3, 208.5, 211.1, 907; 416/132 R, 132 B, 196 A, 194, 195, 235, 237, 238, 244 R, 244 D, DIG. 6

[56] **References Cited**

U.S. PATENT DOCUMENTS

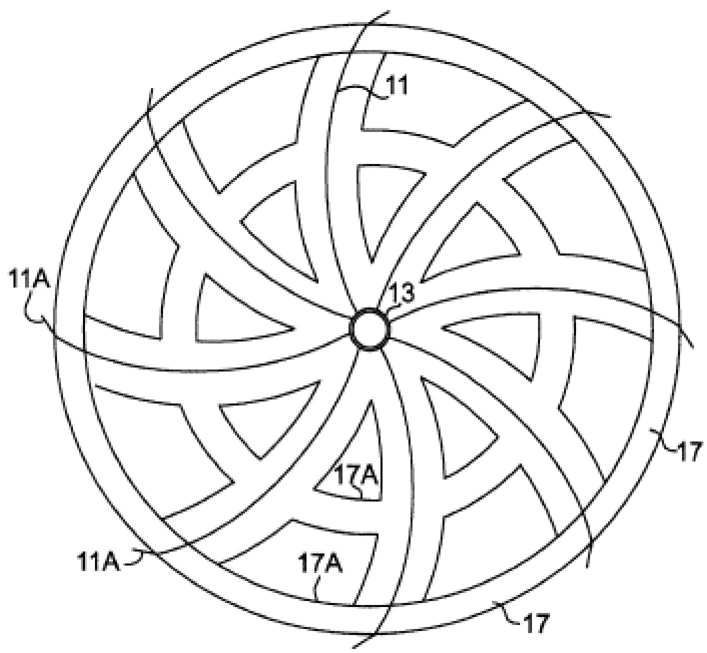
3,938,907	2/1976	Magoveny et al.	415/141
4,236,866	12/1980	Zapata Martinez	415/2 R
4,365,929	12/1982	Retz	415/2 R
4,575,311	3/1986	Wood	416/170 R
5,133,637	7/1992	Wadsworth	415/4.4
5,380,149	1/1995	Valsamidis	415/2.1
5,391,926	2/1995	Staley et al. .	
5,463,257	10/1995	Yea	290/55
5,553,996	9/1996	Farrar	415/2.1

Primary Examiner—Edward K. Look
Assistant Examiner—Matthew T. Shanley
Attorney, Agent, or Firm—Dean P. Edmundson

[57] **ABSTRACT**

Wind turbine apparatus is described for converting wind energy into electrical energy. The apparatus includes a rotatable central shaft, a plurality of rotor blades attached to the central shaft, and a plurality of convex airfoils spaced around the periphery of the rotor blades. The ratio of the number of rotor blades to the number of airfoils is at least 1.25 to 1. The size of the apparatus may vary, and the apparatus is useful in a variety of applications and environments. It is very efficient in converting wind energy to electrical energy. It may be operated even in very high wind conditions.

16 Claims, 8 Drawing Sheets



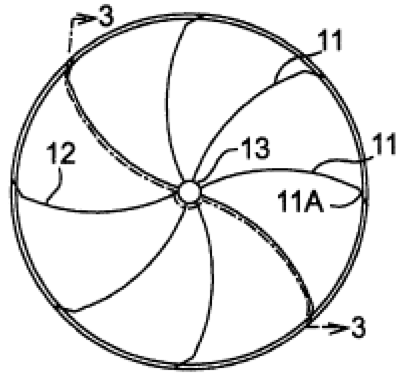


FIGURE 2

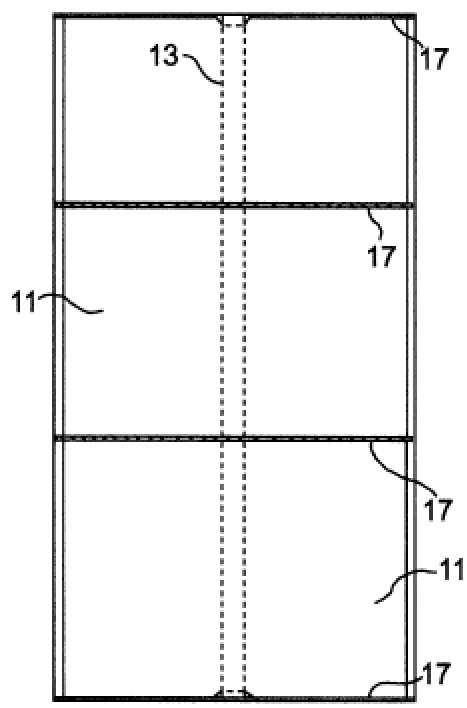


FIGURE 3

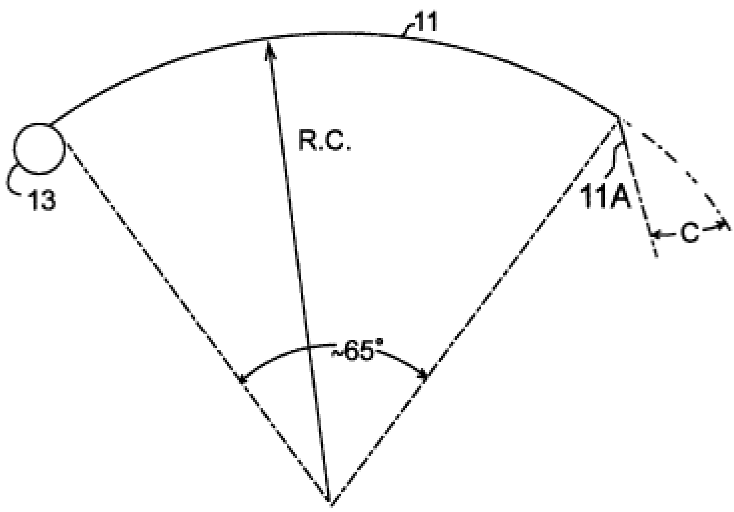


FIGURE 2A

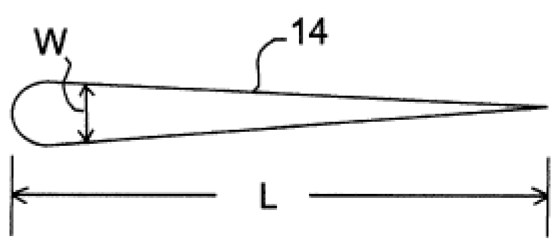


FIGURE 4A

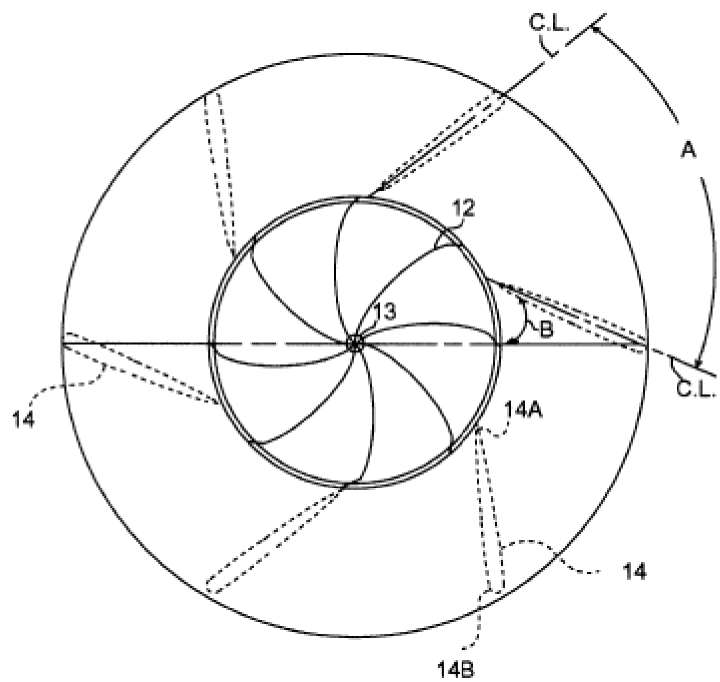


FIGURE 4

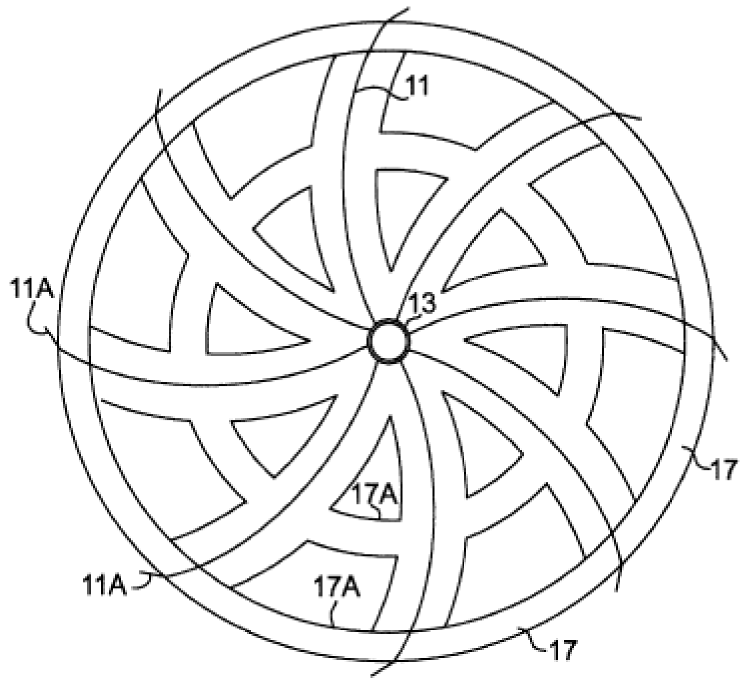


FIGURE 5

Works Cited

Adams, Rod. "Nuclear Power for Galena, Alaska." 20 March 2005. Atomic Insights. 9 October 2007 <http://www.atomicinsights.com/AI_03-20-05print.html >.

"Alternative Energy Sources and Storage." 2005. Physics at Indiana University Southeast. 9 October 2007 <http://physics.ius.edu/E/Alternative.html >.

Apricus Solar. Apricus Solar Collectors. 27 February 2008 <http://www.apricus.com/html/solar_collector.htm>.

Australian Institute of Energy. "Fact Sheet 6: Hydro Electricity." (November 2003).
"Backrounder on New Nuclear Plant Designs." 2007. United States Regulatory Commission. 9 October 2007 <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/new-nuc-plant-des-bg.html>.

Baron, Gerardo P. "Phillippine Bio-Digester Home Biogas System (HBS)." October 2007. www.biofuelswork.com. 7 February 2008 <http://www.appropedia.org/Home_biogas_system_%28Philippine_BioDigesters%29>.

Beck, Fredric. "Renewable Energy Fact Sheet ." Environmental and Energy Study Institute (2006).
—. Renewable Energy Fact Sheet: Geothermal. Washington D.C.: Environmental and Energy Study Institute, 2006.

Bergamasco, Rosangela, Maria Cristina Rizk and Celia Regina Granhen Tavares. "Anaerobic Codigestion of Fruit and Vegetable Waste and Sewage Sludge." International Journal of Chemical Reactor Engineering (2005): 1-10.

"Biodiesel Basics." 2007. Biodiesel Board. 17 September 2007 <http://www.biodiesel.org/resources/biodiesel_basics/default.shtm >.

"Biodiesel on the Farm." 2007. Biodiesel Board. 17 September 2007 <http://www.biodiesel.org/markets/far >.

"Biomax Power System." 2007. Community Power Corporation: Our Products. 9 October 2007 <http://www.gocpc.com >.

Blankinship, Steve. "Power Engineering: Workers Falling Off at Yucca Mountain." June 2007. Expanded Academic ASAP. Gale. Worcester Polytechnic Institute. 9 October 2007 <http://find.galegroup.com/itx/start.do?prodId=EAIM >.

Bloomquist, R. Gordon. "Commercial and Industrial Heat Pump Case Studies." 2002.

Brown, Valerie J. "Biogas: A Bright Idea for Africa." May 2006. Environmental Health Perspectives. 2 February 2008 <http://www.ehponline.org/members/2006/114-5/innovations.html>.

Bryner, Michelle. "Jet Propellant Goes Green. Chemical Week 169.29." 5 September 2007. General Reference Center Gold. Gale. Worcester Polytechnic Institute. 9 October 2007 <http://find.galegroup.com/itx/start.do?prodId=GRGM >.

California Energy Commission . Geothermal Heat Pumps. 2006. January 2008 <http://www.consumerenergycenter.org/home/heating_cooling/geothermal.html>.

California Fuel Cell Partnership. "Hydrogen Fueling Stations." 8 October 2007 <http://www.cafcp.org/fuel-vehl_map.htm>.

CityRating.com. Average Temperature. 2007. 26 February 2008 <http://www.cityrating.com/citytemperature.asp?City=Worcester>.

Clean Break. Heat-recovery Tech for Drains Hits Home Depot. 22 February 2008 <http://www.renewability.com/images/Power_Pipe.jpg>.

"Conceptual Design of Yucca Mountain Disposal Plan." 2007. United States Nuclear Regulatory Commission. 9 October 2007 <http://www.nrc.gov/waste/hlw-disposal/design.html >.

Corporation, McElvaney Associates. Bioconversion Primer. 2005. 9 February 2008 <http://www.bioconverter.com/technology/primer.htm>.

Current Installed Wind Power. Washington D.C.: United States Department of Energy, September 11, 2007.

Darling, David. "Anaerobic Digestion." The Encyclopedia of Alternative Energy and Sustainable Living (1999).

Design News. "Big Solar: Sun Rises on Solar." (2006).

Dickson, Mary H and Fanelli. "What is Geothermal Energy." Pisa, Italy (February 2004).

Elrod, Scott. "Solar Concentrators." Palo Alto Research Center (2005): 1-5.

Energy Efficiency and Renewable Energy. "FEMP Designated Product: Electric Water Heaters." 2006. Energy Efficiency and Renewable Energy. 24 February 2008 <http://www1.eere.energy.gov/femp/procurement/eep_electric_waterheaters.html>.

"Energy Efficiency and Renewable Energy: Ethanol." 2007. The United States

Department of Energy. 17 September 2007 <http://www1.eere.energy.gov/biomass/ethanol.html >.

Energy Information Administration. "U.S. Energy Consumption by Energy Source." Table 11 and 12: Official Statistics from the U.S. Government (2007).

"Energy Sources- Bioenergy." 2007. United States Department of Energy. 17 September 2007 <http:www.energy.gov/energysources/bioenergy.htm>.

Environmental and Energy Study Institute. "Concentrating Solar Power." Renewable Energy Fact Sheet (2005): 1-2.
—. Renewable Energy Fact Sheet: Hydropower. Washington D.C, May 2006.

"Fact Sheet 9: Geothermal." November 2003.

Fitch, Jonathan. Princeton Wind Farm. Princeton: Princeton Municipal Light Department, 2006.

Fontenot, J.P., L.W. Smith and A.L. Sutton. " Alternative Utilization of Animal Wastes." Journal of Animal Science (1983): vol 57.

FPL Energy. Prototypes Under Test at FPL Parabolic Trough Power Plant. 6 October 2007 <http://www.reflectechsolar.cpm/P1010004.jpg>.

Geurts, Mirjam. Introduction to the main characteristics of human excreta and grey water. 2005.

Gifford, Henry. "Significant Energy Savings at No Extra Cost." Northeast Sun Volume 25, Number 1 Spring, 2007: 13-17.

Greiner, T.H., M.E. Hein and R.J. Smith. "Experimental Methane Production from Animal Excreta in Pilot Scale and Farm Size Units." Journal of Animal Science (1979): vol 48.

Gustafson, David, Ann Kenimer and Bruce Lesikar. University Curriculum Development for Decentralized Wastewater Treatment; Septage-Biosolids. Texas A and M University, December 2004.

Hoffert, M, K Caldeira and G. Benford. "Fourteen Grand Challenges: What Engineers Can Do to Prove We Can Survive in the 21st Century." Mechanical Engineering Power (2003): 10-29.

How Do Wind Turbines Work? 2007. 3 Febuary 2008 <http://www.tech-faq.com/how-do-wind-turbines-work.shtml>.

Inhabitat. "Seville's Solar Power Tower." 8 October 2007 <http://www.inhabitat.com/wp=content/uploads/solarseville.jpg>.

J. Lund, B. Sanner, L. Rybach, R. Curtis, G. Hellström. "Geothermal (Ground-Source) Heat Pumps A World Overview." Renewable Energy World 6 (2003): 1-10.

Jones, Don D., John C. Nye and Alvin C. Dale. Methane Generation from Livestock Waste. Purdue University, 2000.

Kanellos, Michael. "Gas From Manure: Big Plant to Open." 2007. CNETNews.com. 25 September 2007 <http://www.news.com/Gas-from-manure-Big-plant-to-open/2100-1008_3-6119213.html?tag=item >.

Klass, Donald L. "Methane from Anaerobic Fermentation." 9 March 1984. Journal Storage: Science. 4 February 2008 <<http://links.jstor.org/sici?sici=00368075%2819840309%293%3A223%3A4640%3C1021%3AMFAF%3E2.0.CO%3B2-M>>.

Knier, Gil. "How do Photovoltaics Work?" Science at NASA. 8 October 2007 <http://science.nasa.gov/headlines/y2002/solarcells.htm>.

Kristjansdottir, Anna Sigridur. "The Icelandic Hydrogen House." 8 October 2007 <http://www.fa.is/deldir/Liffraedi/ventni/index_clip_image028_0000.jpg>.

"Learning About Renewable Energies: Biofuels." 2007. National Renewable Energy Laboratory. 17 September 2007 <http://www.nrel.gov/learning/re_biofuels.html >.

Lipper, Ilan and Jon Stone. "Nuclear Energy and Society." 1998. University of Michigan. 9 October 2007 <http://www.umich.edu/~gs265/society/nuclear.htm >.

Massachusetts 50m Wind Power. Washington D.C.: United States Department of Energy, February 6, 2007.

Meschke, John Scott. Wastewater Treatment. University of Washington, <courses.washington.edu/h2owaste/notes/ENVH440545_lec1_2007.ppt> Powerpoint 2006.

Micro-Vett. "Fuel Cells: Structure and Operation." 8 October 2007 <http://micro-vett.it/H2/imagesh2/pem_fuelcell.gif>.

National Renewable Energy Laboratory. "Zero Energy Buildings:A Critical Look at the Definition." Conference Paper. June 2006.

National Renewable Energy Labs. "Assesment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts." NREL Report SR-55-35060 (October 2003).
Nave, Carl R. "Hyperphysics." 2005. Department of Physics and Astronomy: Georgia State University. 9 October 2007 <hyperphysics.phy-astr.gsu.edu/.../reactor.html>.

Niwagaba, Charles. Human Excreta Treatment Technologies: Prerequisites, Constraints and Performance. Sweden, 2007.

"Nuclear Energy Overview." 2007. Energy Information Administration: Official Energy Statistics from the US Government. 2 October 2007 <http://www.eia.doe.gov/emeu/mer/pdf/pages/sec8_2.pdf>.

Okafor, Emeka. "KIST Rwanda, Biogas." 2 April 2005. Timbuktu Chronicles. 1 February 2008 <http://timbuktuchronicles.blogspot.com/2005/04/kist-rwanda-biogas.html>.

Parker, Dick and S.K. Gallagher. "Distribution of Human Waste Samples in Relation to Sizing Waste Processing in Space." 1992. SAO/NASA Astrophysics Data System (ADS). 2 February 2008 <http://articles.adsabs.harvard.edu/full/conf/lbsa./1992/0000568.000.html>.

PassivHaus UK. Outline specification for a PassivHaus in the UK. 24 February 2008 <http://www.passivhaus.org.uk/index.jsp?id=669>.

Richard, Michael Graham. "Biogas: Poo-Powered Prison in Rwanda." 4 July 2005. Science and Technology-Treehugger.com. 1 February 2008 <http://www.treehugger.com/files/2005/07/biogas_poopower_1.php>.

Richards, B.S and G.J. Conibeer. "A Comparison of Hydrogen Storage Technologies for Solar-Powered Stand-Alone Supplies: A Photovoltaic System Sizing Approach." International Journal of Hydrogen Energy 32 (2007): 2712-2718.

Schouw, N.L, et al. "Composition of Human Excreta: A Case Study from Southern Thailand." 5 February 2001. Science Direct. 5 February 2008 <http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V78-453X5CH-G&_user=74021&_rdoc=1&_fmt=&_orig=search&_sort=d&view=c&_acct=C000005878&_version=1&_urlVersion=0&_userid=74021&md5=01986f74bb9b71d18b0eb13b4676e79b>.

Shinnar, Reul. "The Hydrogen Economy, Fuel Cells, and Electric Cars." Technology in Society 25 (2003): 455-476.

Shukman, David. "Power Station Harnesses Sun's Rays." 2 May 2007. BBC News. 8 October 2007 <http://news.bbc.co.uk/2/hi/science/nature/6616651.stm>.

"Smaller Modular Gasification." 2007. The United States Department of Energy: Energy Efficiency and Renewable Energy. 17 September 2007 <http://www1.eere.energy.gov/biomass/small_modular_gasification.html >.
"Technology in Action:UK biogas pioneer on solid ground." 16 May 2007. Process Engineering: General Reference Center Gold. Gale. Worcester Polytechnic Institute. 9 October 2007 <http://find.galegroup.com/itx/start.do?prodId=GRGM >.

ThinkQuest. "Solar Cells." 7 October 2007 <http://library.campbellhall.org/mla%20bibliography.htm>.

TMA Wind. 2007. January 2008 <http://www.tmawind.com/index.php>.

"Transporting Nuclear Waste." 2007. United States Department of Energy. 1 October 2007 <http://www.ocrwm.doe.gov/transport/index.shtml >.

USA Today. Hydrogen-filling station opens... In Iceland. 25 April 2003. 8 October 2007 <http://www.usatoday.com/tech/news/techinnovations/2003-04-25-hydro-station_x.htm>.

USBR GOV. "Grand Coulee Dam." 26 September 2006. 1 October 2007 <http://www.usbr.gov/pn/grandcoulee/>.
—. "Hoover Dam Power FAQ." 30 January 2006. 1 October 2007 <http://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html>.

USGBC. What is L.E.E.D? 2007. 6 October 2007 <http://www.usgbc.org/DisplayPage.aspx?categoryID=19>.

Valutech Inc. Alpha Laval Heat Exchangers. 2008. 29 February 2008 <http://www.valutechinc.com/alfalaval1.htm>.

Watkins, Chris. Category: Biogas. 18 October 2007. 7 February 2008 <http://www.appropedia.org/Category:Biogas>.

Were, Elizabeth. Recycling Human Waste for Food Security. Linkoping, Sweden, January 2007.

Werner, Carol. Renewable Energy Fact Sheet: Wind Power. Washington D.C., May 2006.

"What is PBMR?" 2007. Pebble Bed Modular Reactor (Pty) Ltd. 19 September 2007 <http://www.pbmr.com/index.asp?Content=4& >.

Wheldon, Anne and Ashden Judges. "Kigali Institute of Science, Technology and Management, Rwanda 2005." 2005. The Ashden Awards for Sustainable Energy. 2 February 2008 <http://www.ashdenawards.org/files/reports/KIST%20Rwanda2005%20Technical%20report.pdf >.

Wilson, Alex. Consumer Guide to Home Energy Savings. Washington, D.C.: ACEEE, 2003.
Worcester Wind Resources. Worcester, MA: Massachusetts Technology Collaborative, September 2, 2003.

Xinhuanet. 2003. 1 October 2007 <http://news.xinhuanet.com/english/2003-09/01/content_1055970_1.htm>.

"Yucca Mountain Repository." 2007. United States Department of Energy: Civilian Radioactive Waste Management. 1 October 2007 <http://www.ocrwm.doe.gov/ym_repository/index.shtml >.

Zink, John. "Power Engineering: The Hydrogen Economy Needs Nukes." January 2007. Expanded Academic ASAP. Gale. Worcester Polytechnic Institute. 9 October 2007 <http://find.galegroup.com/itx/start.do?prodId=EAIM >.