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Our Capacity to Do Work: the Future of Energy

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THESIS ABSTRACT

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OUR CAPACITY TO DO WORK: THE FUTURE OF ENERGY

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Overwhelming evidence of anthropogenic climate change has surfaced in recent years, and energy consumption is primarily to blame. According to the U.S. Energy Information Administration, the United States alone consumed 97.5 quadrillion British thermal units (Btu) of energy in 2013. We consume so much energy and rely heavily on it in our daily lives, yet as a society we understand so little about it. In a 2009 study sampling 1001 American adults, the majority expressed concern over energy prices and dependence on foreign oil, yet 40% of those sampled could not identify a fossil fuel, and an even higher percentage could not name a renewable energy technology. The purpose of this thesis is to address society's energy illiteracy in order to create an educated public that can act effectively to correct current energy issues.

This thesis outlines the science behind five different energy technologies to show how energy is derived from each technology. The five energy sources addressed are petroleum, biofuels, hydrogen gas, wind energy, and solar energy. Included in the biofuels and hydrogen gas sections are individual research projects conducted at the National Renewable Energy Laboratory and the University of Nebraska-Lincoln, respectively. By focusing on the five aforementioned energy sources, this thesis should provide a brief glimpse at the future of energy.

OUR CAPACITY TO DO WORK: THE FUTURE OF ENERGY

A thesis submitted to
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by

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TABLE OF CONTENTS

LIST OF FIGURES

FIGURE Page

PREFACE

Given the overwhelming evidence of anthropogenic climate change in recent years, I wanted to write a thesis to explore the science behind energy, offering a way for the general public to understand how we consume energy. Energy consumption appears to be the greatest contributor to anthropogenic climate change, and there is a great deal of interest in renewable/alternative energy because people are aware of the negative impact our current energy system has on the climate. However, people's understanding of each renewable energy technology is relatively low. By providing general descriptions of each energy technology, my hope is that readers of this thesis will see the future direction of energy based on the science behind how energy is derived from each energy source.

I would like to thank Dr. Stacy Chamberlin, my thesis advisor, for her tremendous guidance and support throughout the thesis process. Her technical background and shared interest in the future of energy made her instrumental in the writing of my thesis. I also want to acknowledge Dr. Eric Fretz, my thesis reader, for helping me incorporate a humanities perspective into a mostly technical thesis. And last but not least, I want to thank Dr. J. Thomas Howe, Mr. Martin Garnar, Dr. Thomas Bowie, and all others in the Regis College Honors Program who helped me in the completion of my thesis.

I. INTRODUCTION

As a child growing up in western Colorado, I experienced multiple forest fires every summer. I saw some of my favorite towns including Glenwood Springs and Colorado Springs decimated by fire, and it frustrated me that these areas went up in flames so frequently. I wanted to do something about it so that I could enjoy Colorado without concern for the state's future. My parents would tell me that it was beyond my control; that it was just a result of dry climate. To some extent, my parents were right. But I started to realize that we might have some impact on the occurrence of forest fires.

Around the age of 12, I heard about phenomena such as ozone depletion and the greenhouse gas effect. I learned that human consumption of fossil fuels might be to blame for these phenomena that were thought to induce climate change. A number of my family members dismissed the idea, citing their faith to claim that only God has the ability to impact nature so extensively. Al Gore's *An Inconvenient Truth* was a frequent target of family jokes. After learning about the prevalence of human-induced climate change, this was a common reaction. It seemed implausible that people could have done something to put the environment in such dire straits. I held this belief for some time as well, unable to accept the fact that my actions had such a strong impact. But after scientists came to a general consensus that anthropogenic climate change was a reality, and after empirical evidence demonstrating the effects of climate change began to mount, I had to accept the fact that society had contributed to global warming.

Over the past few years many more people, especially in my generation, have accepted the reality of anthropogenic climate change. This trend in society is undoubtedly a good thing. For the most part, we accept the fact that we consume large quantities of fossil fuels and that our vast consumption of these fuels contributes to climate change. Yet in spite of this, our energy literacy in society is low. Many people are unaware of how fossil fuels and renewable energy sources are used to produce something so vitally important to our daily lives. In general, people express the desire to clean up the world or go green, but they do not possess the knowledge about energy to make this possible, or they are not invigorated and infuriated by climate change enough to desire to change the way they act. I will not attempt to use this thesis to convince people that climate change is a reality, as I will work on the assumption that most of my readers believe in the science of climate change. But I will try to increase the reader's knowledge about energy production so that the reader may have the ability to make a difference in the energy market. The purpose of this thesis is to correct the societal lack of energy literacy so that we may have the ability to truly go green.

I will define energy and provide a synopsis of the current energy market. I will discuss various energy technologies and how we derive energy from each of these technologies. I will comment on the efficiency and economic viability of each energy production process, offering a comparison of energy production technologies to provide insight as to why certain technologies dominate the market today. The main focus of this thesis will be on research and development associated with each energy production technology, as this will give us an idea about how to act in a way to reduce the effects of climate change. Discussing these research thrusts will also pave a path for the future direction of energy production and consumption, painting a picture of what our energy future may look like. But first, let us discuss what energy really is.

II. WHAT IS ENERGY?: AN OVERVIEW OF THE CURRENT ENERGY MARKET

Our lives involve energy in some capacity daily. It is something we rely on to travel, to cook, to heat, to cool, and to live in general. From a social standpoint, energy is understood as what keeps us "active" or "boosted." We use terms like "energized" to describe a feeling of invigoration or empowerment. We are aware of the fact that energy impacts us daily. So if energy is something so vital to our daily lives, why do we know so little about it? In a study analyzing energy literacy of secondary students in New York State, it was found that 73% of the 3708 students questioned were concerned about current energy problems[1]. Although the students were concerned about the future of energy, a relatively low number of them understood current energy issues and behaved in a way to address current energy issues. Only 42% of the secondary students had knowledge of the current energy technologies, and only 65% of students with a knowledge of current energy technologies acted in a way that reflected their knowledge of energy consumption[1].

A lack of energy literacy is not characteristic of just our youth. In a 2009 study sampling 1001 random American adults, the vast majority expressed concern over energy prices and dependence on foreign oil for transportation fuels[2]. However, 40% of the adults could not identify a fossil fuel, an even higher percentage could not name a renewable energy technology, and 56% inaccurately believe that nuclear energy contributes to global warming[2]. The purpose of this thesis is to address society's energy illiteracy in order to create an educated public that can act effectively to correct current energy issues.

So what exactly is energy? Before college, I perceived energy as some abstract, elusive entity that we somehow used to power our lives. I saw this entity as something that we extracted from resources, and we were only aware of the fact that these resources provided energy from empirical observation. But this definition of energy is woefully wrong. From a physical standpoint, energy is the capacity to do work. But this type of work should not be confused with the societal definition of work. Work as it relates to energy is the ability of something to act against an opposing force over some distance. When thinking about this in terms of travel, we use work to apply a force against the friction force caused by the road over some distance that we drive. The energy we use for this work is derived from the combustion of the gasoline we put in our engines. We'll investigate the combustion of gasoline in more detail later, but this is a general illustration of energy and work.

Energy, however, is not just related to work. We use a variety of forms of energy. These include, but are not limited to, thermal energy (energy from heat), radiant energy (energy from light), and kinetic energy (energy from motion)[3]. Energy can also come from electrical, chemical, nuclear, and gravitational sources[3]. These forms of energy can be categorized into two types of energy: stored (potential) energy and working (kinetic) energy, each of which are vital for energy consumption in our current energy market[3].

Units of energy are often expressed in joules, which are equal to the amount of work done in applying a force of 1 Newton over a distance of 1 meter. In an American setting, however, the most common unit of energy is a British thermal unit (Btu), which is the amount of energy needed to heat or cool a pound of water by one degree Fahrenheit. One Btu is approximately equal to 1055 joules. This formal definition of energy units is understandably boring, but these units of energy will be important for the expression of national energy consumption statistics later on in this thesis.

We often use energy and power interchangeably, but it is worth noting that there is a difference between the two. Power is the rate at which energy is supplied, often expressed in watts (1 watt = 1 joule per second). Because power is an expression of energy's rate, energy prices are often calculated in terms of power, as the price of the energy we consume is directly dependent on the amount of time that we are consuming that energy source.

We use a variety of resources for energy, but we rely primarily on petroleum, natural gas, and coal for current energy consumption. Of the 97.5 quadrillion Btu consumed by Americans in 2013, 82% of the energy consumed was derived from the three aforementioned resources[3]. Petroleum, natural gas, and coal are all examples of fossil fuels, which are created over millions of years by the action of the Earth's core on the remains of deceased plants and creatures[3]. Petroleum, natural gas, and coal consumption will be further explained in the next three sections. Although the three aforementioned resources dominate the current energy market, renewable energy technologies and nuclear energy play an important role in energy consumption, and their stake in the energy market is likely to increase rapidly in the next ten to twenty years. The figure below provides a summary of U.S. energy consumption in 2013, as data about U.S. energy consumption in the year 2014 is currently unavailable.

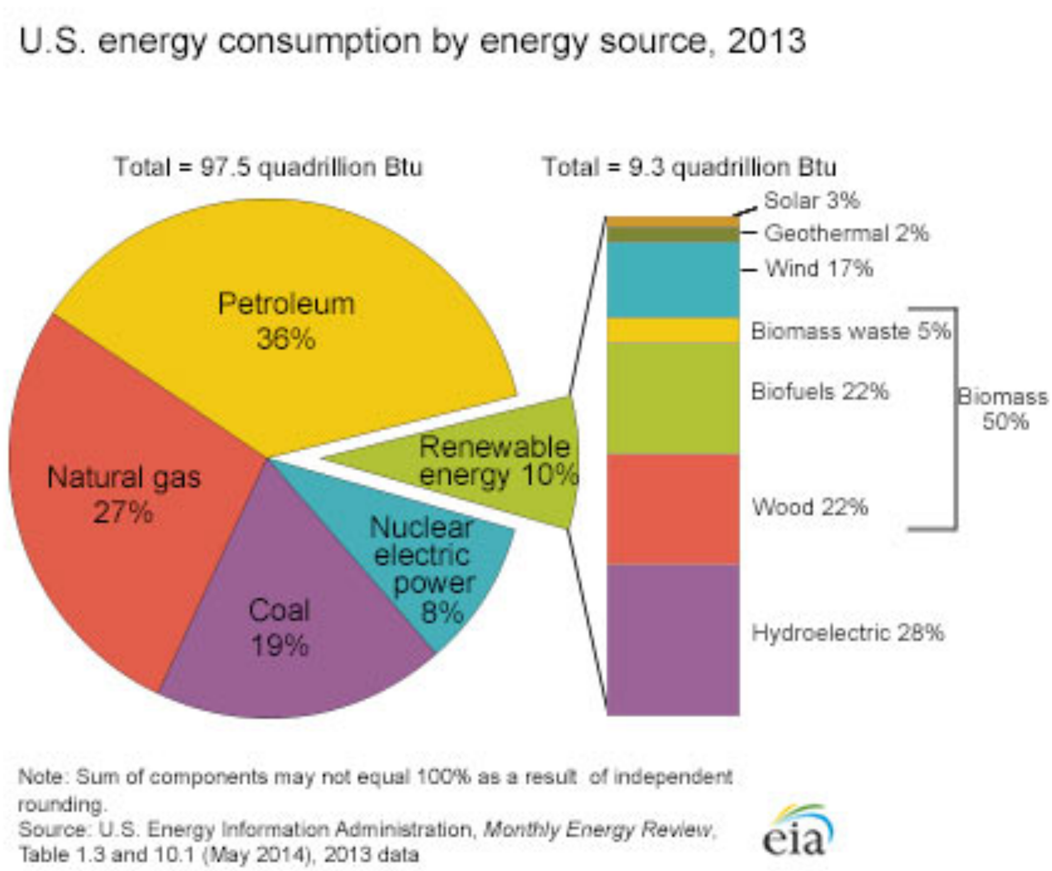


Figure 1. 2013 U.S. Energy Consumption by Energy Source. Adapted from the U.S. Energy Information Administration.

In the energy market, we distinguish renewable from nonrenewable energy sources. Renewable energy sources are sources that are easily and quickly replenished, and non-renewable energy sources are those that are not easily reproduced[3]. It is intuitive for us to rely on renewable energy sources, as they can readily be recreated, but nonrenewable energy sources dominate the energy market due to low cost and ease/efficiency of energy production from these resources. The five most common renewable energy technologies are wind energy, solar energy, energy derived from biomass, geothermal energy, and hydroenergy. Each renewable energy technology will be discussed in detail in the following sections.

In the sections to follow, I will provide a description of each energy technology including an overview of how energy is produced from the resource; how efficient the energy production process is; how large of a stake the technology has in the current energy market and will have in the future market; and what research is being conducted to improve the technology. I will put particular emphasis on research in biofuels and hydrogen gas, as I have conducted research projects in these two areas at the National Renewable Energy Laboratory and the University of Nebraska-Lincoln, respectively. I will also discuss public policy regarding natural gas in detail, as I was published as a co-author on a paper about this topic during my time at the University of Nebraska-Lincoln.

III. PETROLEUM

Overview

Petroleum, the Latin word for "rock oil," is a fossil fuel that is made as a result of the natural decay of prehistoric plant and animal remains. It consists of hundreds of different hydrocarbons (compounds containing the atoms carbon and hydrogen) including many alkanes, cycloalkanes, and aromatic hydrocarbons. Petroleum exists as a liquid (crude oil) and as a gas (natural gas). It is developed as the result of the settling of prehistoric plant and animal remains among sand, silt, and rock. As layers of sedimentary rock trap the organic remains of biological organisms, high pressure and temperature conditions result in a source rock that is heated to form petroleum. Petroleum is held within the layers of sedimentary rock, gradually moving upward within the Earth through porous spaces in the rocks to form reservoirs, which consist of porous, permeable rock structures that can hold large amounts of petroleum. These reservoirs can range from hundreds to thousands of feet in depth below the Earth's surface. According to the 2010 report from the U.S. Energy Information Administration (EIA), the United States has the 14th-largest oil reserve by volume with 19.2 billion barrels[4]. Given the volume of oil and natural gas available in present reserves, the Society of Petroleum Engineers estimates that we will have oil for 44.6 more years and natural gas for 66.2 more years at current consumption levels[4]. However, we are unaware of the oil reserves that are yet to be found, so this estimation is subject to variation.

Drilling Process

https://www.youtube.com/watch?v=uNATp0aCkQg

To extract oil and natural gas from underneath the Earth's surface, a motor is used to rotate a drill bit attached to pipe into the Earth's surface. This drill bit is equipped with special "teeth" that allow it to penetrate massive rocks. Once the drill bit reaches the well of interest, a fluid referred to as drilling mud goes into the pipe, continues to travel down the pipe until it reaches the reservoir containing oil and/or natural gas, and comes back up to the surface through the wellbore, which is the newly created hole in the Earth. This drilling mud consists of clay, water, and other chemical additives. These chemical additives are used to ensure that the drilling mud retains its composition under the high temperature and pressure conditions characteristic of the Earth well below its surface. Drilling mud is used to extract bits of rock created during the drilling process so that they can be removed before the petroleum is extracted. The drilling mud is also used to equilibrate pressure within the wellbore and ensure that fluids other than petroleum do not travel up the wellbore.

Once a wellbore has been created, the wellbore is cased with cement and steel to prevent contamination of the ground water table. Once geochemists verify that a drilled well has reached a reservoir using something called a logging tool, small diameter tubing is sent down the cased wellbore to serve as a channel for petroleum to flow up through the wellbore. A perforating gun consisting of several explosives is sent into the small diameter tubing. These explosives are then detonated at the depth of the reservoir, creating perforations in the petroleum reservoir to connect the wellbore to the reservoir. To facilitate the flow of petroleum through the wellbore, fracturing of the perforations within the reservoir is utilized. The process of fracturing used for well drilling is shown in figure 2 below.

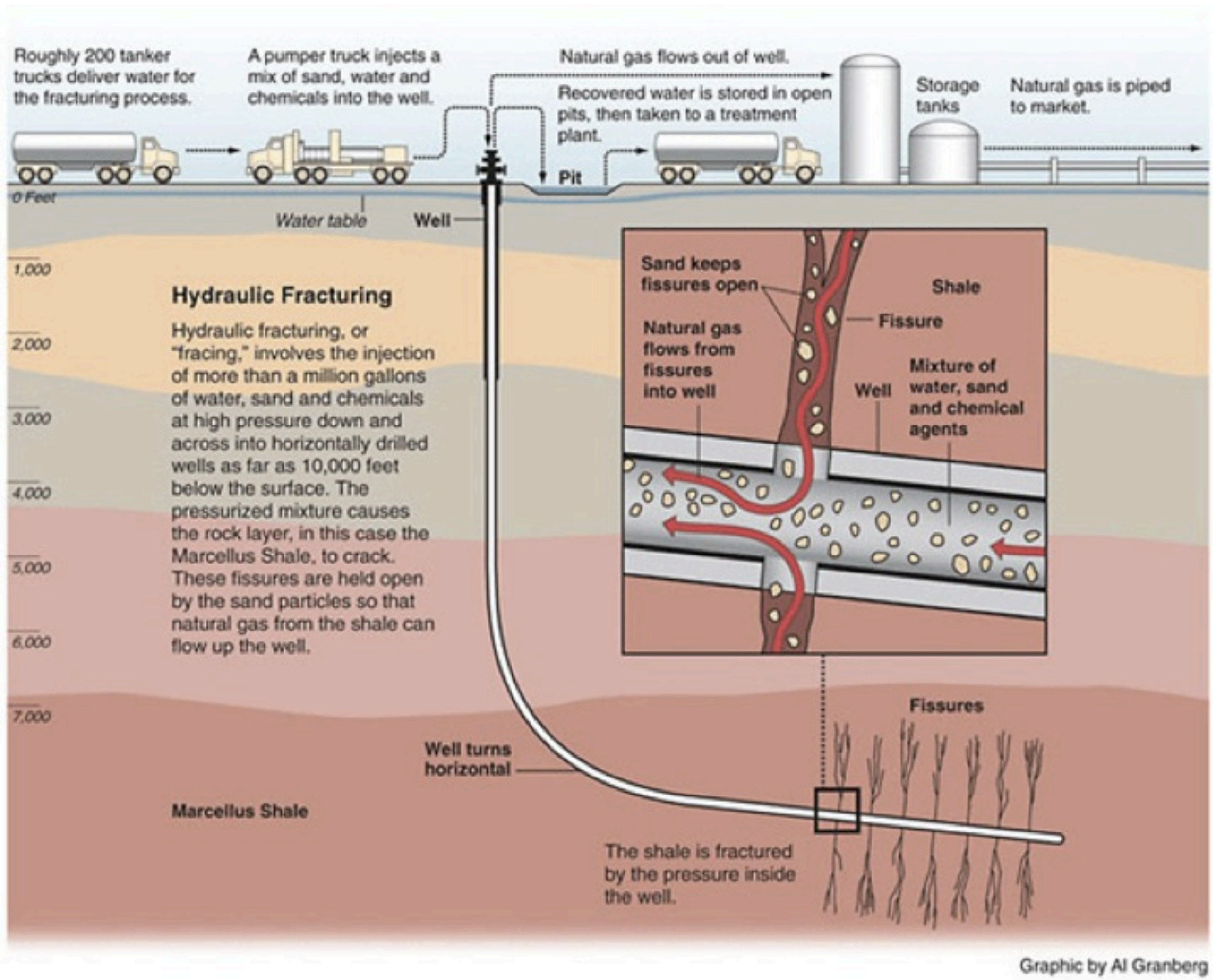


Figure 2. Hydraulic Fracturing Figure. Adapted from Al Granberg.

This involves the use of a highly pressurized mixture of sand, air, and fluids to introduce cracks into the reservoir. Due to the high pressure within the reservoir, the petroleum is able to readily flow through the wellbore because it exhibits a much lower pressure than that of the reservoir. To regulate flow, a device called a "choke" is introduced to the wellbore. After a well has been fully established, an assembly of control and safety valves referred to as a "Christmas tree" is used to top the well. A pump jack is added to the well to separate natural gas from oil, and the two substances are stored separately. A photograph of a complete petroleum well is shown in Figure 3 below.

Figure 3. Complete Oil Well. Adapted from Al Granberg.

Oil drilling technology used to only allow direct vertical drilling, but due to recent advances in drilling technology using horizontal fracturing, reservoirs within 5 miles of a drilling site are accessible. According to the Society of Petroleum Engineers, the process of drilling a single well can cost more than $15 million dollars depending on the depth of the well that is drilled[4].

Research Objectives

In order to mitigate the environmental impact that oil drilling has on the environment, oil and gas companies are examining ways to drill multiple wells in one location to limit surface damage and to use environmentally friendly chemicals for the stimulation of well production. In addition, researchers are assessing the efficacy of heaters used to convert rock formations into a liquid that can readily be drained[4]. However, this practice may present irreparable damage to the rock formations lying beneath Earth's surface. In addition, drilling mud and the process of hydraulic fracturing require immense amounts of water.

Given the scarcity of water, scientists and engineers are researching ways to treat the water used by oil companies to make it potable. One of the major issues associated with petroleum combustion is the emission of carbon dioxide. Research efforts have focused on the sequestration of carbon dioxide, storing combusted carbon dioxide in power plants and industrial facilities. Carbon dioxide can then be processed, compressed at high pressure, and injected into space between rock grains below the Earth's surface[4].

Outlook

Several oil and gas companies speak about the environmental friendliness of oil and natural gas and optimistically discuss research in the oil and gas industry to make the extraction and combustion of petroleum safer for the environment. However, the ambitions of these companies regarding these research projects are potentially unauthentic. Many oil and gas companies write about research investigating safer chemical additives for drilling mud, yet none of this research is published in a journal accessible to a general scientific audience. They also claim on their websites that research to remove sulfur dioxide and other unsafe impurities in petroleum is being conducted, but it doesn't seem that this research is mass-producible at an industrial level. In general, it appears that oil and gas companies are simply trying to justify or rationalize the continued consumption of petroleum without actually attempting to mitigate the negative environmental impact of the combustion of petroleum. The petroleum industry is so profitable that this is all that is really necessary. So how do we make oil and gas companies accountable? We continue to pursue legislation similar to the Clean Air Act to force oil and gas companies to reduce the carbon emissions that are produced from the combustion of petroleum.

The estimated number of years for which oil and natural gas could continue to be used at current consumption rates is approximately half a century for each energy resource, and this really seems like a long number of years for the millennial generation. We likely will not experience a shortage of petroleum in our lifetimes. However, these figures are very subject to variation. We are unaware of how many reservoirs are present under the Earth's surface, so the Society of Petroleum Engineers may overestimate just how long we will have oil and gas. And the estimated number of years left for petroleum are calculated based on consumption of oil and natural gas in the year 2010. Since 2010, petroleum consumption has continued to increase to meet societal energy demands. Given that nearly a third of petroleum consumption is used for purposes other than energy production, we ought to conserve the amount of petroleum used for energy so that we will continue to have enough essential petroleum for other uses in our society.

Because natural gas releases fewer greenhouse gases than other fossil fuels, natural gas has been proposed as an alternative source of energy because it is better for the environment in comparison to fossil fuels and it is profitable for energy companies[5]. However, the hydraulic fracturing methods employed to extract natural gas have been shown to be harmful to the environment[5]. Because water is used for hydraulic fracturing, and water is a particularly scarce resource, we must consider ways to purify/treat the water used for hydraulic fracturing so that it is potable and reusable. Additionally, the use of natural gas leads to the emission of carbon buried in the ground, introducing new carbon into the environment that is not already circulating in the biosphere[5]. This debunks the societal misconception that using natural gas is good for the environment, as it is not carbon neutral. It is also, like oil, non-renewable because it is derived from plant and animal remains over periods of time ranging millions of years. Although our energy demands could be met using natural gas for a period longer than fifty years, we will ultimately run out of natural gas and oil. The advantages and disadvantages of natural gas must be considered, as the future of natural gas will play an influential role in the future of bioethanol production and several other renewable energy technologies. In the future energy market, given the environmental appeal of natural gas in comparison to oil, the future short-term energy market will likely feature a great deal of natural gas consumption. The benefits (or lack there of) of this energy market trend are yet to be seen.

IV. BIOFUELS

Video-Biofuels

https://www.youtube.com/watch?v=-ck3FYVNl6s

Video-Algae-to-Fuels

https://www.youtube.com/watch?v=IxyvVkeW7Nk

Overview

Using ethanol from biomass conversion on a petrochemical scale has been proposed as an effective alternative fuel source. Biomass in this case is a generic term for any biological material that can be processed for energy production, and it is often high in cellulose content, as cellulose is a carbohydrate that yields high energy emission when combusted[6]. Through thermochemical conversion processes such as gasification and gas conversion, along with biochemical conversion, of biomass, this process can be used on a national scale to produce bioenergy in the form of ethanol and syngas[7]. Ethanol is a fuel that can be used in gasoline to decrease carbon emissions, while syngas is a byproduct of the combustion of cellulosic biomass that has a chemical composition similar to natural gas[7]. The benefit of this gas in comparison to natural gas is that the natural gas does not have to be extracted from beneath the ground, and the use of syngas does not increase the amount of carbon circulating in the biosphere. Hence the process of biomass conversion to ethanol offers a way to produce multiple energy sources in one step. However, under current conditions, society would have to make sacrifices in diet to compensate for the land used to produce biomass[7]. Asking citizens to do this is impractical, which is why certain ways to improve the efficiency of this process are being investigated to make biomass conversion to ethanol feasible. A step in the process of biomass conversion to ethanol that is of particular focus in current research is the use of microbes to convert cellulose and cellulose derivatives to ethanol. Metabolic engineering of microorganisms that are used to convert biomass to ethanol is of interest, as this process is utilized to make cellulase enzymes that more readily degrade cellulose and increase the efficiency of the biomass conversion process. Crucial to the microbial conversion method is the ability of microbes to respond to stressful conditions such as high temperature, high pH, high salinity, etc., as the reaction conditions for biomass conversion are often very high in temperature. One microbe that has been investigated is *Thermoanaerobacter tengcongensis*, a thermophilic bacterium that has thermostable enzymatic activity[8]. Chaperonins GroESL are stress-response proteins that have been shown to improve cellular tolerance of various stresses when overexpressed[8]. The use of these proteins to protect microbes under high temperature conditions provides an interesting approach to prevent degradation of microbes under these reaction conditions.

The more active effort in metabolic engineering of microbial organisms has been in the creation of enzymes used in biofuel metabolism. *Thermotoga maritima*, a hyperthermophilic bacterium found in geothermally heated sea floors, produces molecular hydrogen at a high yield, and this organism has been proposed as a source of biogas production. The ability of this bacterium to produce hydrogen gas and to partake in biological processes at very high temperatures has led to the idea of inserting a gene encoding for cellulase into the organism so that it can be used to metabolize cellulose to ethanol[9]. Similar efforts have been proposed for other organisms with thermostable enzymatic activity. The benefit of inserting cellulase into the organism is that the degradation of cellulose to ethanol can be improved, but hydrogen gas can also be collected as a byproduct of this reaction. This would offer another energy source that can be collected from the process of biomass conversion to ethanol.

A significant issue associated with the conversion of biomass to ethanol is the difficulty in degrading cellulose. Cellulose is a complex carbohydrate that forms a polymer, making it very hard to degrade. To mitigate this issue, pretreatment with dilute acid and hydrolysis have been proposed to make cellulose more susceptible to cellulase activity. This hydrolysis process is accomplished using ionic liquids (ILs). However, the high ionic strength of ILs often denatures the enzymes that are involved in cellulosic ethanol production. It has been suggested that organisms with hyperthermophilic activity, such as *Thermotoga maritima* and *Pyrococcus horikoshii*, express IL-tolerant enzymes that can be used when pretreating cellulose with ionic liquids so that the pretreatment step can readily be combined with the enzymatic conversion event[10]. The ability to combine these two steps provides an intriguing opportunity to dramatically increase biomass conversion efficiency.

Another way to improve cellulose degradation is the combined use of cellulosomes and cellulases. Cellulosomes are protein complexes that contain hemicellulases and cellulases with multiple catalytic units per complex[11]. These cellulosomes were first isolated from the anaerobic bacterium *Clostridium thermocellum*, and the ability of these cellulosomes to bind multiple substrate units makes them an intriguing prospect for cellulose degradation to ethanol. However, these cellulosome complexes are very large (in the range of mega Daltons), making them hard to use for penetration of cellular membranes and walls. Using free cellulases can solve this problem because cellulase enzymes are much smaller in comparison to cellulosomes. Cellulosomes and cellulases have been shown to have a synergistic effect on cellulose degradation, as the cellulases can penetrate cell membranes/walls so that cellulosomes can enter the cell to better metabolize cellulose[11]. Using this combination offers a way to improve the process of biomass conversion to ethanol and other biofuels.

The biggest concern for bioethanol production is the effect it will have on national and international food supply. Roddy addresses this issue extensively, claiming that societal dietary changes must be implemented to make bioethanol production work. The majority of bioethanol currently produced is from corn, which could eventually lead to a shortage of food if this process is pursued with corn as the biomass. However, extensive research has been conducted to see what other substrates can be used for biomass in this process. *Gracilaria sp.*, a red alga, when used with the budding yeast *Saccharomyces cerivisiae in situ*, yields ethanol by fermentation at a very high yield, making it a potential feedstock in a biorefinery for ethanol production[12]. This algal strain is particularly effective as a biomass substrate because it has high cellulose, glucose, and galactose content[12]. Similar research has been conducted with other algal strains to test their effectiveness as biomass substrates. Other biomass substrates that have been studied extensively are switchgrass, corn stover, and poplar. Each of these organisms expresses high concentrations of cellulose, hemicellulose, and lignin in their cell walls, which make them ideal substrates for biomass conversion to biofuels.

Many research projects have been pursued to try to improve the efficiency of biomass conversion to ethanol, and several of these projects are very promising.

<u>Biofuel Research Thrust-Enzymatic Conversion (National Renewable Energy Laboratory)</u>

One way biomass can be converted to sugars that can be fermented or otherwise converted to biofuels is from the use of cellulases. Cellulases are enzymes that essentially have the ability to breakdown large cell wall components of plants to make sugars. Enzymes are proteins that have catalytic activity in a chemical reaction that occurs in a biological organism. This process is called enzymatic conversion (or biochemical conversion) of biomass. In order for this process to occur, multiple types of cellulases are needed to degrade different products to make these sugars. The cellulases used to convert biomass to biofuels are expensive, so research has focused on increasing the efficiency of these enzymes to reduce cost. Cellulases are very expensive because cellulose possesses a very rigid, fibrous structure that is difficult to breakdown, so the enzymes used for this conversion process are very expensive. The complex structure of cellulose is shown in Figure 4 below, indicating the difficulty that is presented in the deconstruction of cellulose.

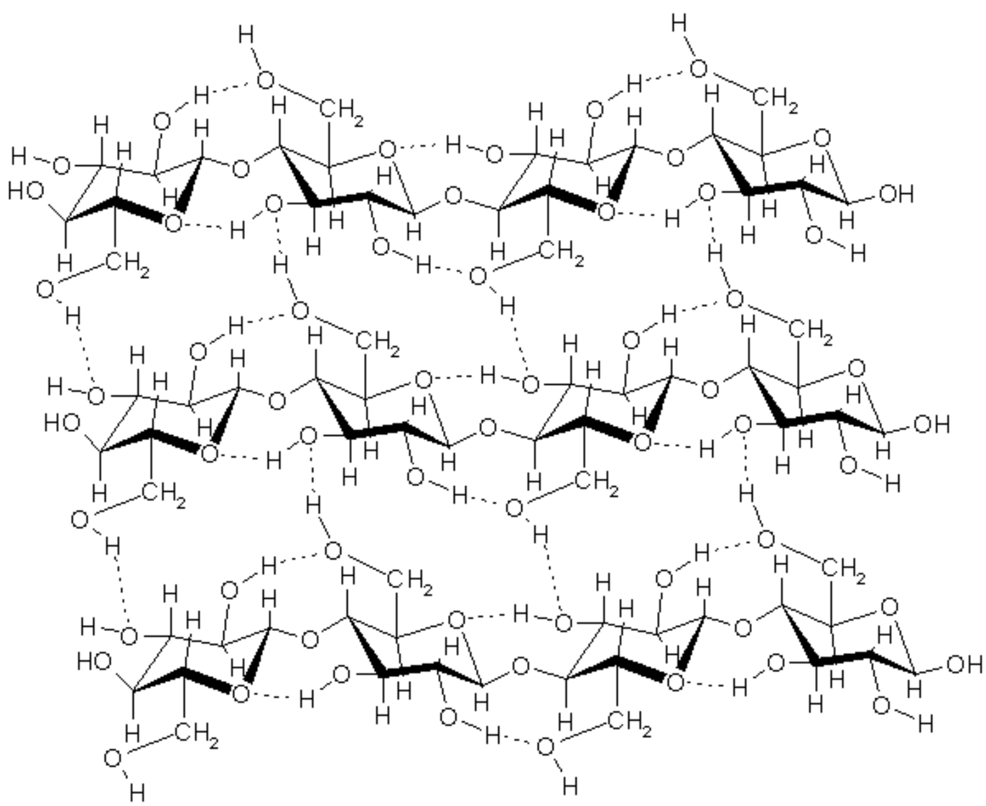


Figure 4. Structure of Cellulose. Adapted from http://www.doitpoms.ac.uk/tlplib/wood/structure_wood_pt1.php.

One such effort to reduce cost has investigated the cellulosome, which is a complex that organizes several types of cellulases in one location. Thus the cellulosome allows all the steps in enzymatic conversion to occur in one place. Another benefit to the cellulosome is that it does not need to be synthesized in a lab, as it is produced biologically by *Clostridium thermocellum*, a bacterium that lives in sea vents. The drawback to the cellulosome, however, is that it is very large and it has difficulty penetrating the cell walls of plants due to its size. The cellulosome must have some ability to penetrate plant cell walls because cellulases must be active on both the interior and the exterior of the cell walls to effectively break them down. The purpose of my research at the National Renewable Energy Laboratory was to see if smaller, genetically modified cellulosomes had an enhanced capability to penetrate cell walls in order to improve the conversion process. I investigated if this was the case by examining the interactions between plant cell walls and the cellulosome under a high-performance microscope. This microscope is called a transmission electron microscope (TEM). A TEM utilizes a high-emission electron beam shining down on a sample. This technique shows high contrast for heavy regions of a sample containing a lot of electrons. In order to examine these interactions, I used an antibody to tag different components of the cellulosome so that they could be seen under the microscope. Antibodies are the actors in the immune system, which bind viral proteins and other components of viruses to tag them for degradation. This particular antibody was designed to recognize the different components of the cellulosome as viral proteins so that the cellulosome bind the antibodies. These antibodies were conjugated with gold particles. Gold is a heavy metal with a high number of electrons, so these gold particles yield high resolution and high contrast photographs of a sample. Gold particles appear as black dots in photographs taken with a TEM. The components I attempted to identify were A2 cohesin and OlpB, both of which are proteins on the cellulosome. I chose to identify these two components of the cellulosome due to the architectural structure of the cellulosome. The cellulosome features both primary and secondary scaffoldins, which are essentially branches coming off the protein. The cellulosome has one primary scaffoldin and several various secondary scaffoldins. The primary scaffoldin is the longest branch of the protein complex possessing the most cellulases, whereas the secondary scaffoldins are much shorter and possess fewer cellulases. Each scaffoldin of the cellulosome uses cohesin and dockerin proteins to glue and anchor cellulases to the cellulosome. A2 cohesin is a very common protein in the primary scaffoldin of the cellulosome, so this component of the cellulosome was used to show a presence of the primary scaffoldin in a sample. The OlpB protein is characteristic of the secondary scaffoldin of the cellulosome, so this component of the cellulosome was used to identify the presence of the secondary scaffoldin in the sample. The images I captured for this analysis are in Figures 5 and 6 below. For this study, we utilized four different construct of the cellulosome. The first construct was the DSC3 cellulosome, which is considered the wild-type cellulosome that does not have any of the primary or secondary scaffoldins knocked out. The second construct was the CTN5 cellulosome, which has all the secondary scaffoldins of the cellulosome knocked out. For this reason, we did not expect to see black dots in photographs taken with the TEM for this construct using the OlpB antibody. The third construct was the DSC11 cellulosome, which has the primary scaffoldin of the cellulosome knocked out. For this reason, we did not expect to see black dots in photographs taken with the TEM for this construct using the A2 cohesin antibody. The fourth construct was the CTN7 cellulosome, which has both the primary and secondary scaffoldins knocked out. We did not expect to see black dots in photographs of these samples with either the OlpB antibody or the A2 cohesin antibody. Figure 5 shows photographs of samples using the A2 cohesin antibody while Figure 6 shows photographs of samples using the OlpB antibody. The first row of each of these figures shows images of the enzyme microbial substrate interface, which is the area of interaction between the cellulosome and the cell walls of plants. The second row of each of these figures shows images of the cell walls of switchgrass, a plant that was chosen to assess the activity of the cellulosome. The third row of each of these figures shows images of *Clostridium thermocellum* cells. *Clostridium thermocellum* is the bacterium that makes the cellulosome.

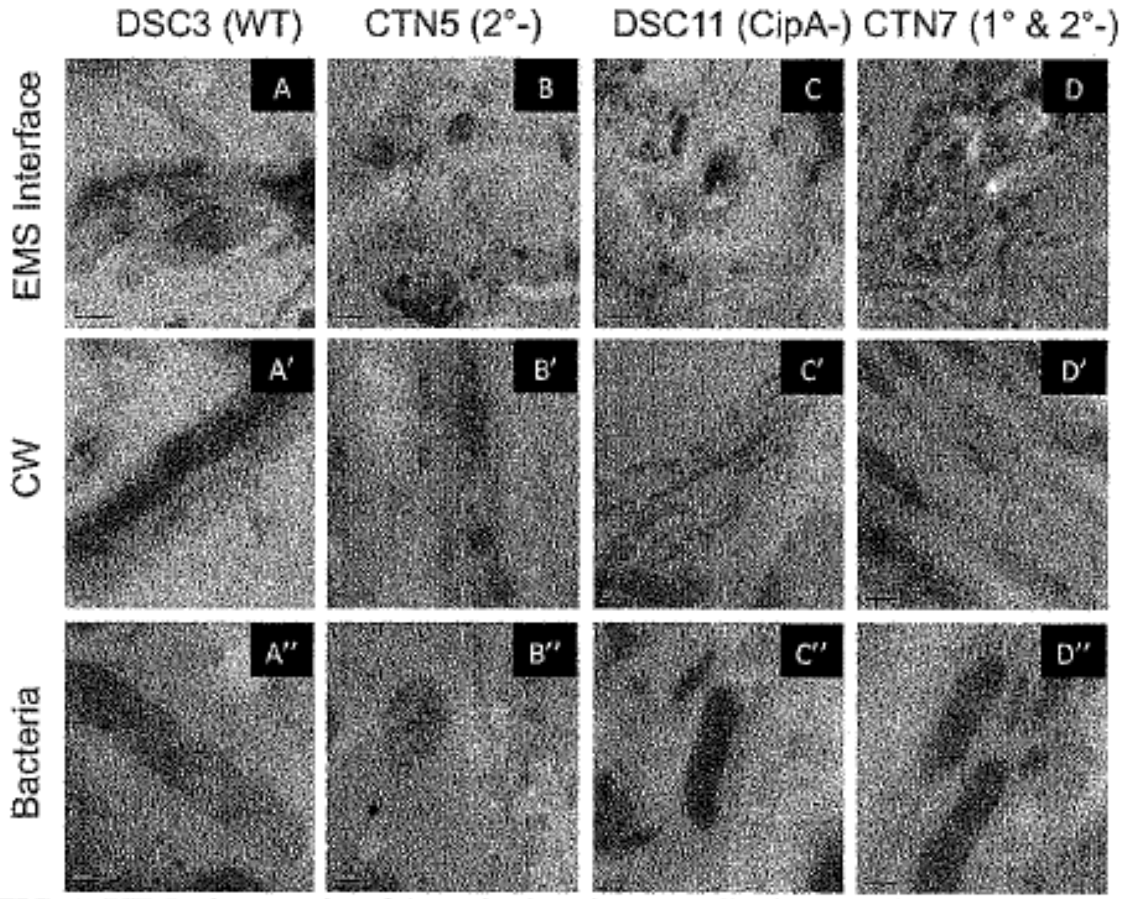


FIG. 1. TEM micrographs of A2 cohesin primary antibody-treated DSC3 (A-A''), CTN5 (B-B''), DSC11 (C-C''), and CTN7 (D-D'') cellulosomes. The micrographs show the locations of cellulosomes in the EMS interface (A-D), corn stover CW (A'-D'), and *C. thermocellum* cell surfaces (A''-D''). Micrographs of the EMS interface show evidence of an interaction between corn stover CW and bacterial cell surfaces for each cellulosomal architecture (A-D). Corn stover CW show similar cellulose deconstruction mechanisms for each cellulosomal architecture (A'-D'). Scale bars A, C, D=1 μm, B=0.5 μm, A'-D', A''-D''=200 nm.

Figure 5. Images of Modified Cellulosomes Treated with an Antibody Binding the A2 Cohesin for Identification.

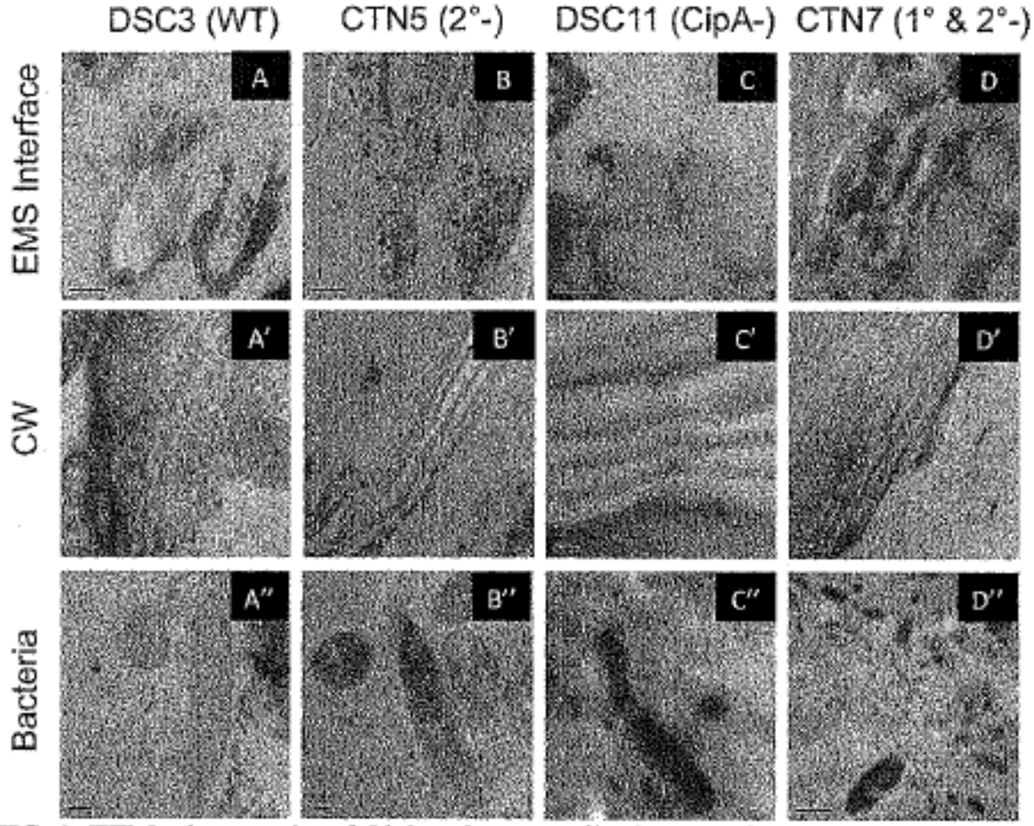


FIG. 2. TEM micrographs of OlpB primary antibody-treated DSC3 (A-A''), CTN5 (B-B''), DSC11 (C-C''), and CTN7 (D-D'') cellulosomes. The micrographs show the locations of cellulosomes in the EMS interface (A-D), corn stover CW (A'-D'), and *C. thermocellum* cell surfaces (A''-D''). Micrographs of the EMS interface show evidence of an interaction between corn stover CW and bacterial cell surfaces for each cellulosomal architecture (A-D). Corn stover CW show similar cellulose deconstruction mechanisms for each cellulosomal architecture (A'-D'). Scale bars A-D=1 μm, A'-D', A''-D''=200 nm.

Figure 6. Images of Modified Cellulosomes Treated with an Antibody Binding OlpB for Identification.

Although the resolution of these images is low as shown, the images demonstrated that smaller, genetically modified cellulosomes were better able than the normal cellulosome to penetrate cell walls. However, they lost some of their ability to break down cell wall components to sugars because they lacked some of the cellulases needed for optimal activity. These crucial cellulases are enzymes that possess the ability to deconstruct cellulose into multiple different sugars. These results suggested that all cellulases needed to be present in the cellulosome to be fully active. These results also indicated that the primary scaffoldin is more important to the cellulosome than the secondary scaffoldins, as the CTN5 construct that lacked the secondary scaffoldins was more effective than the DSC11 construct that lacked the primary scaffoldin at deconstructing cellulose in switchgrass cell walls. Further studies at the National Renewable Energy Laboratory will focus on knocking out non-essential components of the cellulosome to see if these smaller cellulosomes can remain totally functional. Future studies will also look at quantifying the images from these samples to get concrete values for the difference in deconstruction of cellulose by each cellulosome construct.

V. HYDROGEN GAS

Hydrogen Gas Research Thrust-Hydrogen Gas Production by Bacteria (University of Nebraska-Lincoln)

Certain bacteria produce high quantities of hydrogen gas, offering a potential source of hydrogen gas for energy production. However, most of these bacteria do not produce hydrogen in high enough quantities to be cost-effective for mass production of hydrogen gas. For this reason, research has focused on ways to increase the amount of hydrogen gas produced by these bacteria. One bacterium of interest is *Thermotoga maritima*, an organism that lives in hot sea vents. Because this bacterium lives in such hot environments, it can be used in hot combustion processes including the production and consumption of hydrogen gas. The issue with this bacterium is that genetic manipulation of the organism is difficult. For some reason, no evidence of replacement of genetic material has been shown in the organism. The purpose of my research at the University of Nebraska-Lincoln was to see if replacement of genetic material was possible. My lab had isolated a strain of the bacterium that did not produce uracil, which is a crucial compound used in the synthesis of nucleic acids. This strain had a deletion in its DNA, making the insertion of new DNA into this location possible. A schematic of how this might be possible is shown in Figure 7.

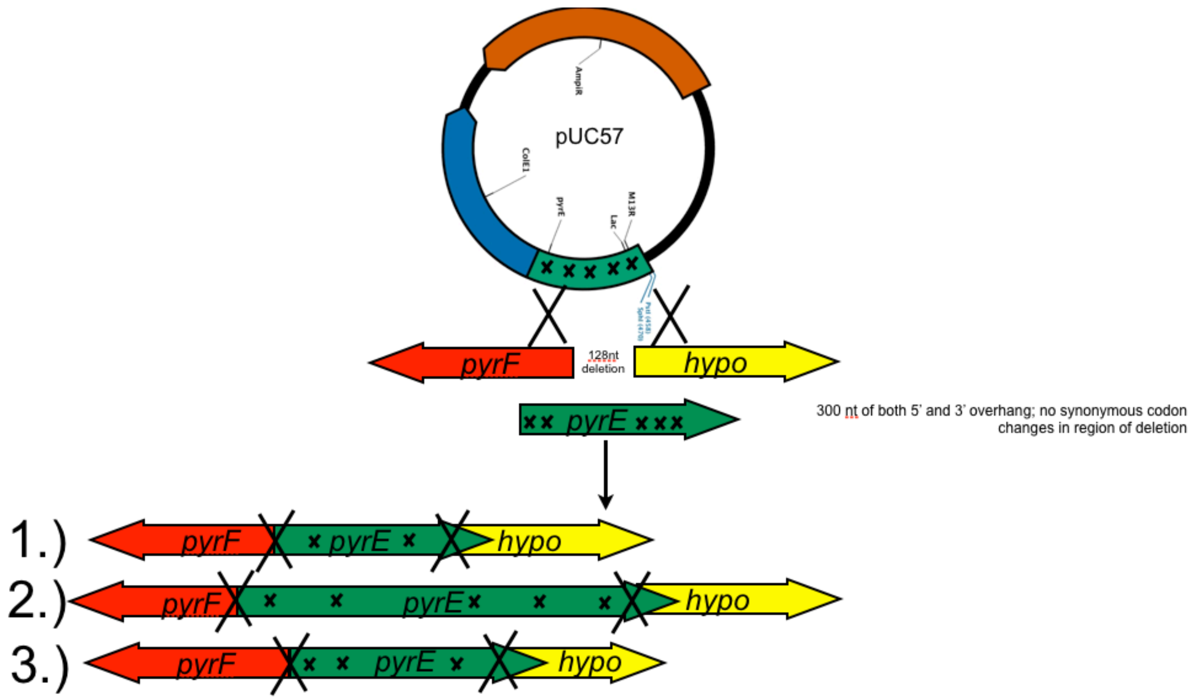


Figure 7. Schematic Representation of New Gene Insertion into *Thermotoga maritima*.

I attempted to insert smaller versions of the gene that allows uracil to be produced at this location in the bacterium's DNA sequence. After DNA was isolated from bacteria in which we attempted to insert the new gene, we ran DNA samples in a DNA gel to identify if the insertion worked. The picture of this DNA gel is shown in Figure 8 below.

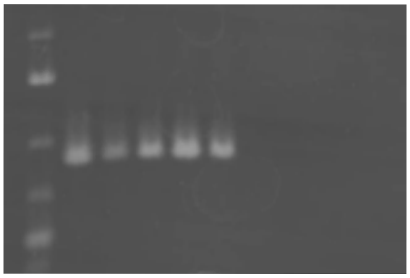


Figure 8. DNA Gel Showing Presence of New Smaller Gene in *Thermotoga maritima.*

This experiment proved that insertion of a new, smaller gene was possible and that nearly 400 base pairs of the DNA in the gene are not needed to produce uracil. This means that potentially more than 400 base pairs of new DNA can be inserted into the bacterium at the location of the deletion. A gene that can be used to increase the amount of hydrogen gas produced by the bacterium could be inserted as this new genetic material, hopefully making cost-effective mass production of hydrogen gas possible in *Thermotoga maritima*

VI. WIND ENERGY

Video-Wind Turbines

https://www.youtube.com/watch?v=tsZITSeQFR0

Overview

I technically should include wind energy in the following section because wind energy is an indirect form of solar energy that I neglected to discuss in the solar energy section. Wind is solar energy in that winds result from the Sun's uneven heating of Earth's atmosphere, along with abnormalities in Earth's surface and Earth's rotation. Wind energy is electric energy harnessed from the kinetic energy produced by wind, and it is often collected using a wind turbine. I'm sure most of the readers are familiar with wind turbines, but they are essentially the opposite of fans. Fans use electricity to produce wind, whereas wind turbines use wind to make electricity. There are two types of wind turbines that utilize different axes to collect the kinetic energy from wind. The first and most common wind turbine is the horizontal-axis wind turbine (HAWT), similar in structure to a traditional windmill[13]. The second is the vertical-axis wind turbine (VAWT) that has blades that spin perpendicular to those of a HAWT when exposed to wind. Its design looks similar to an eggbeater. An illustration of both a HAWT and a VAWT is shown in Figure 9 below.

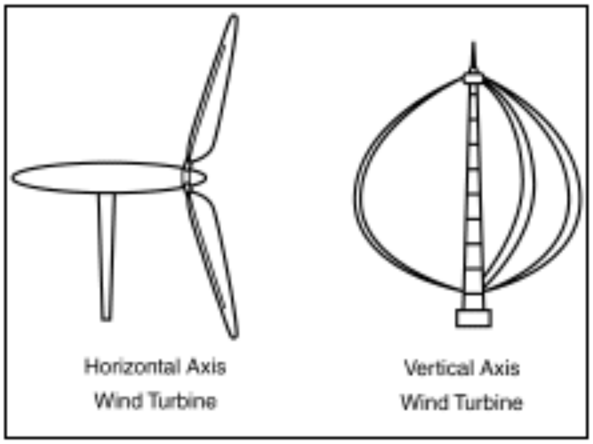


Figure 9. Illustration of Blade Design for the Horizontal-Axis Wind Turbine (HAWT) and the Vertical-Axis Wind Turbine (VAWT). Adapted from http://www.solacity.com/smallwindtruth.htm.

HAWTs include a rotor (composed of all the blades) that converts the wind's kinetic energy to rotational shaft energy, a drive train (including a gearbox attached to a generator that converts the rotational kinetic energy to electricity), and a tower providing support for the rotor and drive train[13]. All these components of a HAWT are shown in detail in Figure 10 below.

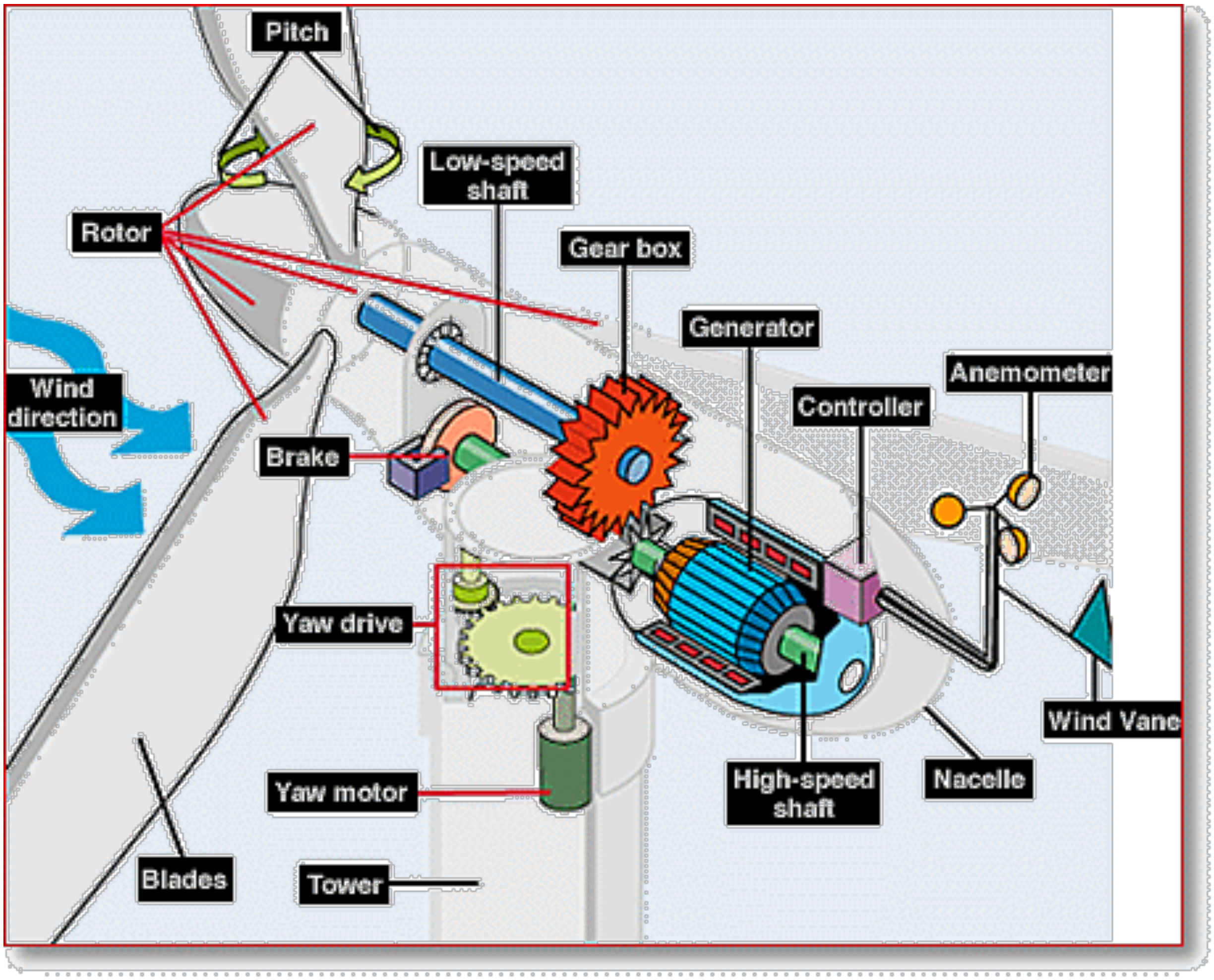


Figure 10. Components of a Horizontal-Axis Wind Turbine (HAWT). Adapted from http://windeis.anl.gov/guide/basics/turbine.html.

In order to harness substantial kinetic energy from the wind, wind turbines must be large. HAWTs often have blades the span a football field in the length and a tower standing 20 stories high[13]. Although this immense size may not be aesthetically pleasing, the size of a HAWT allows it to produce enough electricity for 1,400 homes[13].

Outlook

The benefits of using wind energy are obvious. Wind turbines passively harness the kinetic energy of wind, so there are few energy costs associated with the use of wind turbines. The greatest expense regarding wind energy is the initial investment to produce a wind turbine, but given a long time of operation based on the cost of a "life-cycle" for a generator, wind turbines are extremely cost-competitive with other energy-generating technologies. Also, the energy produced does not generate any carbon emissions. In 1990, the U.S. Department of Energy estimated that California's wind plants offset carbon emissions by 2.5 million pounds of carbon dioxide[13].

However, there are some drawbacks to wind energy as well. Environmentalists find large wind turbines aesthetically displeasing and dislike the fact that the blades of wind turbines have killed numerous bats and birds. Wind is also a temperamental energy source, and intermittency makes it impossible to rely solely on wind energy for our energy production needs. In addition, the greatest wind resource in the United States is in the Midwest, which is far from the major electrical grids on the East Coast and the West Coast. If the United States were to rely on wind energy in the future, establishing the infrastructure to connect wind turbines to electrical grids would be a daunting and costly task.

So what's the future of wind energy? Potentially harnessing offshore breezes using the less common VAWT. Traditionally, wind energy has been collected using land-based HAWTS. However, VAWTs possess the ability to reduce the cost of collecting wind energy offshore due to a lower turbine center of gravity, a simpler machine structure, and greater variability in the sizes of turbines that can be produced[14]. A low center of gravity helps VAWTs stay afloat in water, eliminating the problem of HAWTs tipping over offshore[14]. Also, the drivetrain of a VAWT is closer to the surface in comparison to a HAWT, making maintenance easier[14]. Given that the VAWT's blades rotate around the vertical axis, it is also unnecessary to have a control system to move the blades in the direction of the wind. The advantages of VAWTs for harnessing offshore wind are summarized in Figure 11 below. The future of wind energy undoubtedly will involve the use of offshore turbines to collect an ample wind resource offshore.

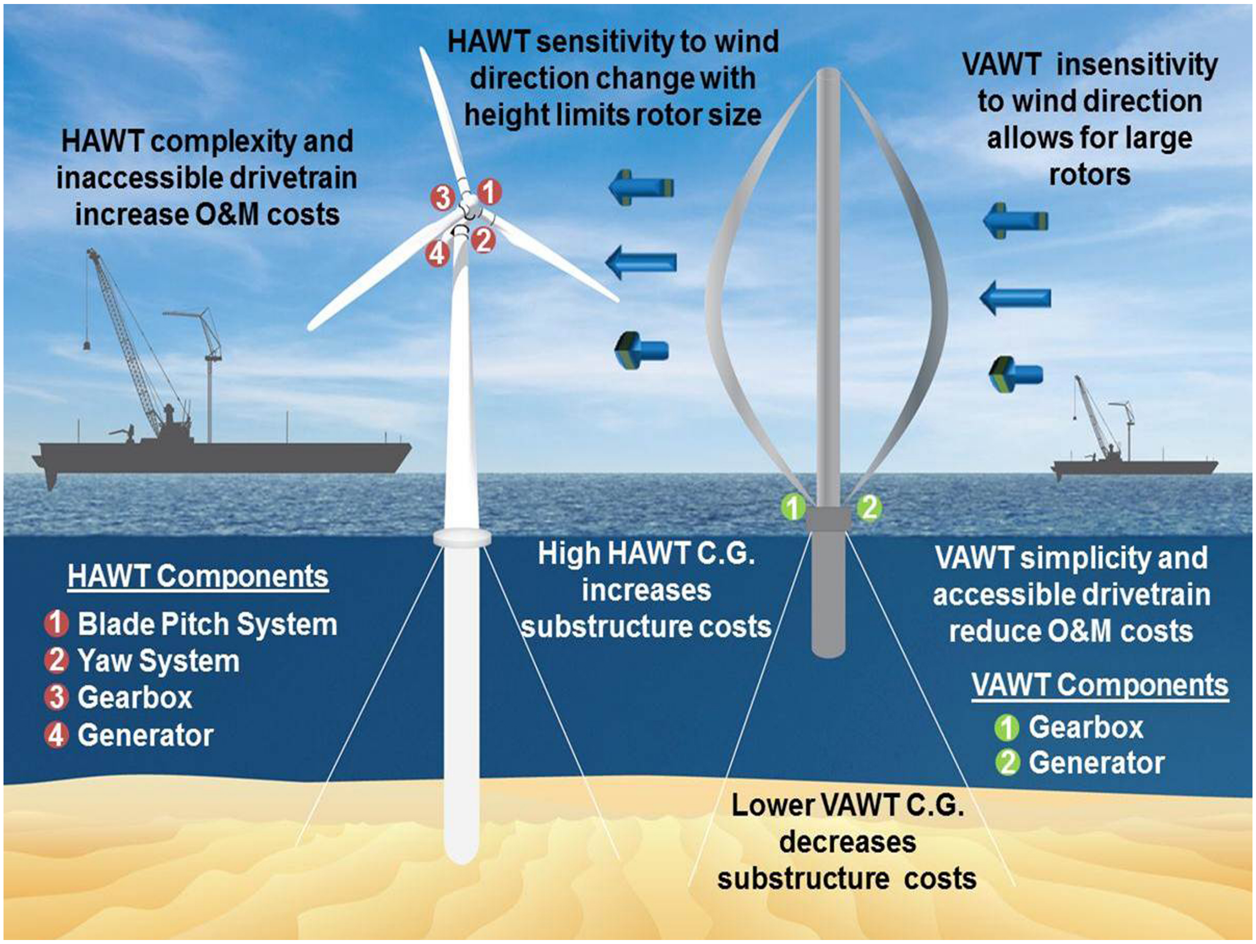


Figure 11. Horizontal-Axis Wind Turbines (HAWTs) vs. Vertical-Axis Wind Turbines (VAWTs) in the Collection of Offshore Wind. Adapted from https://share.sandia.gov/news/resources/news_releases/images/2012/vawt01.jpg.

VII. SOLAR ENERGY

Video-Solar PV

https://www.youtube.com/watch?v=0elhIcPVtKE

Video-Concentrating Solar Power

https://www.youtube.com/watch?v=rO5rUqeCFY4

Overview

Solar energy is described as any energy that is derived from the Sun's irradiance in which the energy from the Sun is converted into chemical or thermal energy. This definition seems obvious, but it is important when considering the four different ways to harness solar energy. The one that society is most familiar with is photovoltaics (PV) in which photovoltaic solar panels are used to absorb photons from the Sun and convert them to usable electricity. The others are not as well known. These include solar heating and cooling, concentrating solar power (CSP), and passive solar[15]. Solar heating and cooling utilizes thermal energy from the Sun to heat water and provide space heating/cooling, displacing the need for electricity or natural gas[15]. CSP collects thermal energy from the

Sun using mirrors so that the mirrors reflect light to a thermal energy-transferring substance. This thermal energy is then collected and used to power steam turbines. Passive solar collects heat from the Sun and distributes the heat throughout either residential or commercial buildings without the use of mechanical or electrical devices[15]. Solar energy has captured the interest of the general public because of its massive potential and undeniable renewability and sustainability. However, all forms of solar energy currently only account for less than 1% of the current energy market. This percentage seems staggeringly low for something that has received so much attention, but it is the great potential of solar energy that has garnered so much attention. Below, this thesis will discuss this great potential and some of the reasons why solar energy has yet to reach its full potential. PV and CSP are the more interesting renewable energy technologies that will ultimately see an increased role in the energy market in the future, so this thesis will now focus solely on PV and CSP.

Photovoltaics (PV)

Photovoltaic (PV) devices use materials called semiconductors to generate electricity from sunlight. In PV devices, the electrons of the semiconductors are excited and travel through an electrical circuit. This motion of electrons is used to power a local electrical device or sent to an electrical grid[16].

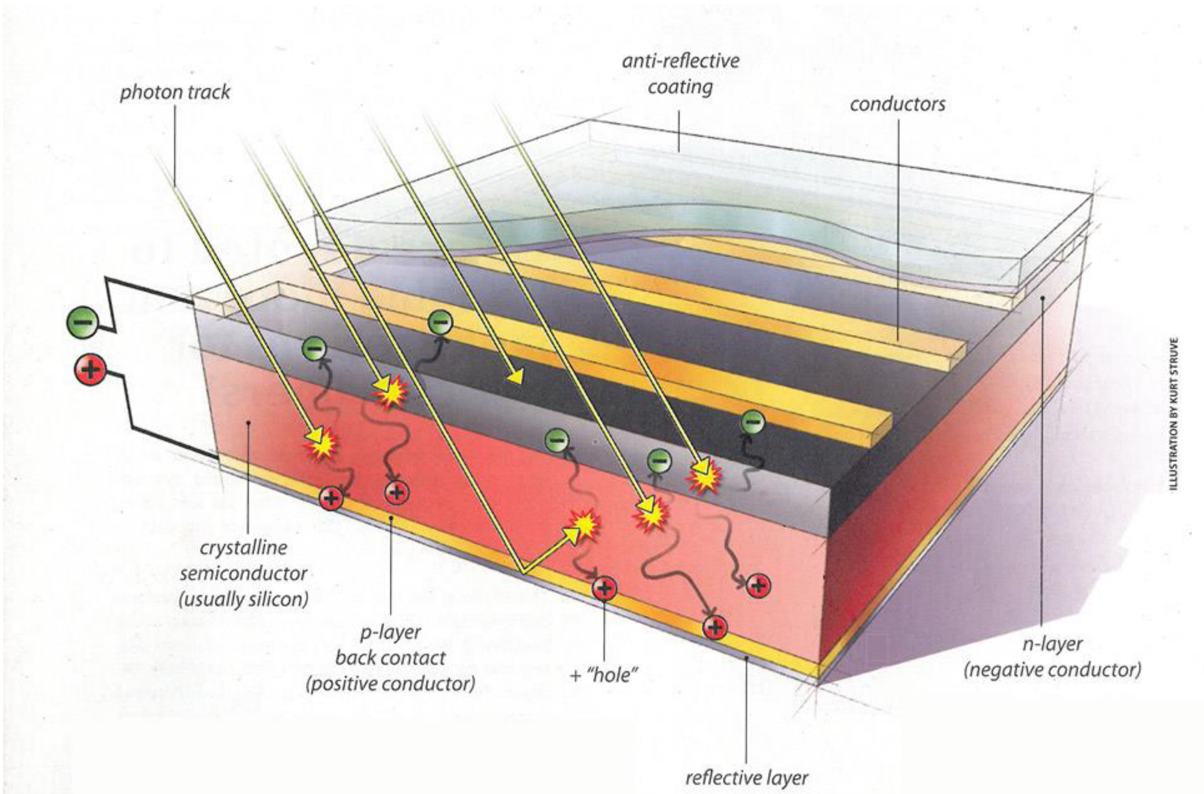
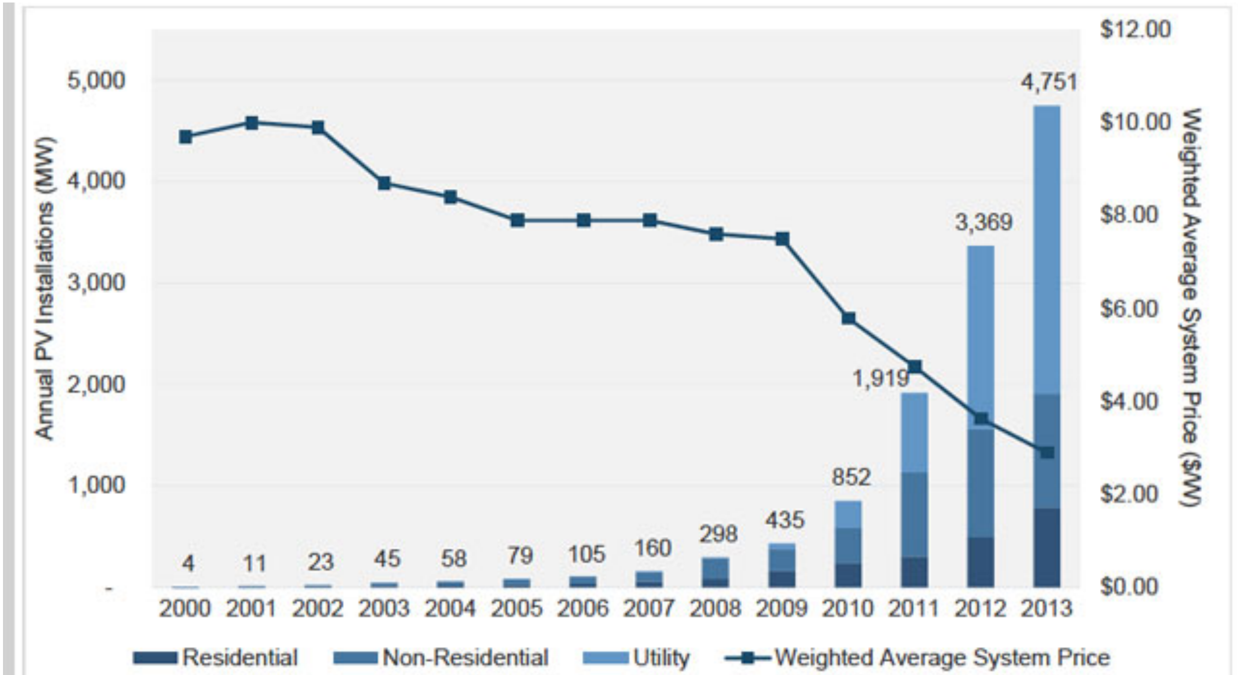


Figure 12. Illustration of a crystalline silicon photovoltaic (PV) solar cell. Adapted from https://www.seia.org/policy/solar-technology/photovoltaic-solar-electric.

Photons from the Sun ionize the semiconductor material in a PV panel, and this process causes electrons on the surface of the semiconductor to flow to a positive "hole" (see Figure 12 above). An electrical current is created by this positive hole as the negatively charged electrons are attracted to the positive hole[16]. The downfall of PV technology is the lack of efficiency in this process, as not all photons sufficiently ionize the electrons of the crystalline semiconductor. This lack of efficiency results from the occasional reflection of light, which is why solar cells often use an anti-reflective coating (see Figure 12 above). In addition, it is often only visible light that is able to ionize crystalline semiconductor materials, but the Sun irradiates infrared and ultraviolet light as well. Infrared light is too weak energetically to ionize most crystalline semiconductors, and ultraviolet light often creates thermal energy rather than electricity[16]. Ideally, PV solar panels would be able to harness electricity from infrared, visible, and ultraviolet light, but all sources of light have very different characteristics energetically. This makes it very difficult to find a semiconductor material that will be effectively ionized by all three different light sources. Many research objectives focus on finding a semiconductor material, or combination of semiconductor materials, that will increase the efficiency of solar cells by using materials that are more effectively ionized by solar light.

Major interest in PV solar panels was first garnered during the energy crisis of the 1970s, but the high cost of PV devices presented a major challenge to widespread use of PV technology. Prices of PV devices have since fallen rapidly, according to the Solar Energy Industries Association (SEIA). The SEIA estimates that the average price of a completed PV system has been reduced by nearly 33 percent since 2011[16]. Figure 13 below shows the decreased price of PV systems in the United States, along with the increased installation of PV systems that has resulted from this reduced price. Given this current trend, solar cells will likely have decreased prices and increased installation in the near future.



Installations (MW)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Residential	1	5	11	15	24	27	38	58	82	164	246	304	494	792
Non-Residential	2	3	9	27	32	51	67	93	200	213	339	831	1,072	1,112
Utility	0	3	2	3	2	1	0	9	16	58	267	784	1,803	2,847
Total Installations	4	11	23	45	58	79	105	160	298	435	852	1,919	3,369	4,751

Figure 13. U.S. PV Installations and Prices. Adapted from https://www.seia.org/policy/solar-technology/photovoltaic-solar-electric.

The decreased price and increased installation of PV systems can be attributed to new technology regarding semiconductor materials in PV systems. Modern PV systems often utilize crystalline silicon or thin-film organic semiconductor materials. A silicon semiconductor is more efficient, as solar photons ionize more electrons in crystalline silicon. However, crystalline silicon is expensive and has a relatively high manufacturing cost. Thin-film organic semiconductors have low manufacturing costs, but are less efficient than silicon semiconductors. Scientists are now exploring multi-junction (or tandem) solar cells with high efficiency-to-weight ratios that have satellite and military applications.

Concentrating Solar Power (CSP)

Concentrating solar power (CSP) utilizes mirrors to reflect the Sun's light to some thermal receiver that stores thermal energy. This thermal energy is then used to drive a steam turbine to generate electricity. CSP differs from photovoltaics (PV) in that the energy collected is thermal rather than electric. The advantage of collecting thermal energy as opposed to electrical energy is that thermal energy can be stored and used to produce electricity when needed, whereas electricity cannot be stored[17]. In CSP, the thermal energy collected is often transferred to water, causing the water to boil. The steam drives a steam turbine to generate electricity. There are a variety of CSP plants that utilize different mechanisms to collect thermal energy. These include the parabolic trough, the compact linear Fresnel reflector (CLFR), the power tower, and the dish-engine[17]. The parabolic trough system uses curved mirrors, reflecting the Sun's light to a receiver tube composed of a heat transfer fluid. Thermal energy from the Sun is then transferred through the fluid to ultimately boil water. The CLFR uses long parallel rows of flat mirrors to reflect light to a receiver tube elevated above the mirrors. Because the CLFR uses flat mirrors, it is often less costly than a parabolic trough system. A power tower utilizes a central receiver with computer-controlled flat mirrors extending a certain radius out from the central receiver. The power tower system can operate at higher temperatures, thus improving its efficiency in comparison to the parabolic trough system and the CLFR. The dish-engine uses an arrangement of mirrors similar to the parabolic trough system, but it uses a working fluid like liquid hydrogen to drive an engine[17]. Figure 14 below illustrates the four different systems used for CSP.

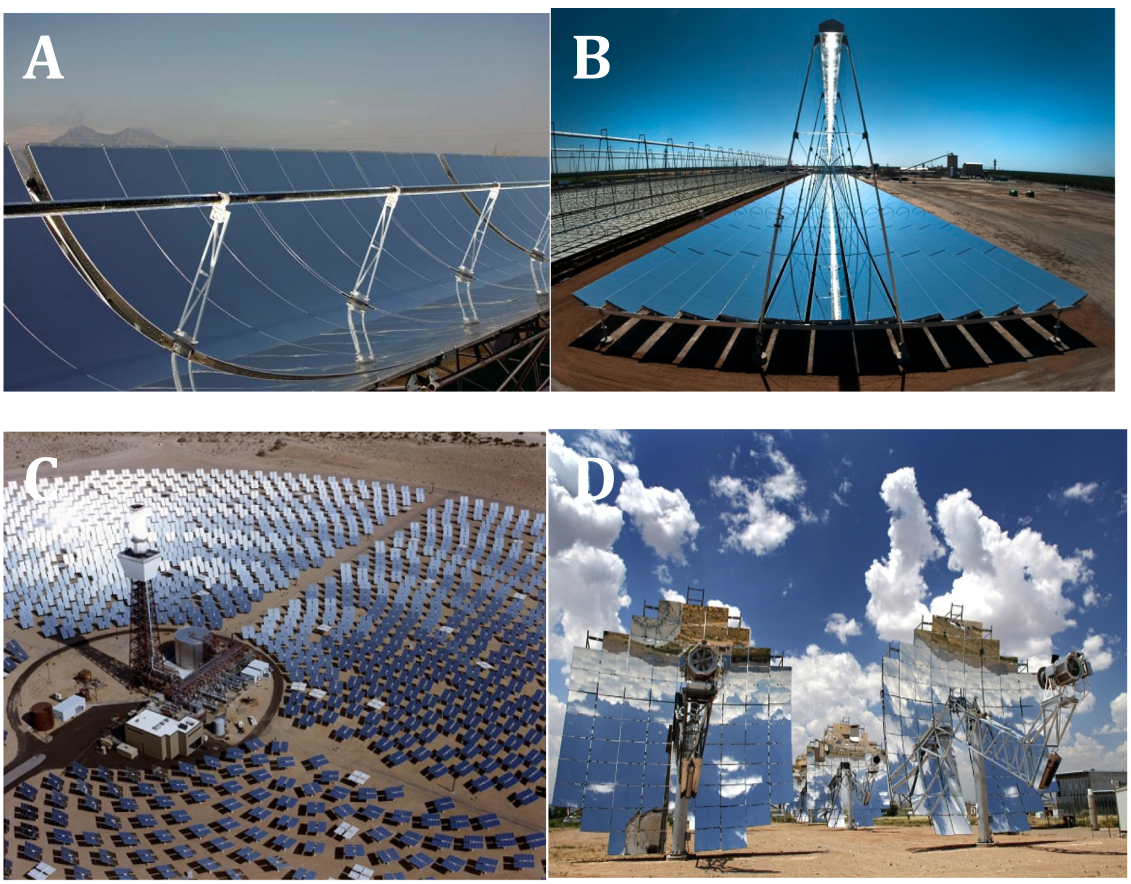


Figure 14. Concentrating Solar Power (CSP) Systems. A.) Parabolic trough system. B.) Compact linear Fresnel reflector. C.) Power tower. D.) Dish-engine. Adapted from https://www.seia.org/policy/solar-technology/concentrating-solar-power.

Outlook

I realize that my summary of the technology behind photovoltaics (PV) and concentrating solar power (CSP) may have been trite, but I present this information in the hope of showing what we can realistically expect from PV and CSP. Most people hear about solar cells and view solar as the future of energy production. But this picture of solar energy may be unrealistic. Solar cells continue to be installed at increasing rates, and the average price of cells continue to drop, but these may be attributed to government subsidies and tax incentive programs that give tax breaks to people with solar cells. Although scientific literature reports increasing efficiency of solar cells, the values for efficiency are often not verified by a third party and may not be reproducible. And even if higher values for efficiency are accurate, the materials used for highly efficient PV cells often cannot be manufactured at an industrial level.

Although PV seems to be the more attractive form of solar energy, CSP could be the future face of solar energy. CSP is valuable in that the solar energy is stored as thermal energy so that it can readily be stored and used later. The photons generated in PV cells cannot be stored and used later. In addition, the materials involved in CSP are often cheaper than the silicon and organic materials used in PV cells. Why not use materials as cheap as mirrors to harness the most convenient energy source at our disposal? Although CSP seems like a logical pursuit, issues such as space and infrastructure inhibit the advancement of CSP. Hopefully these issues will be addressed in the near future.

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