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Essays in Energy

Kaufui Vincent Wong

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Abstract

Essays in Energy is a collection of a number of essays by the same number of engineers. They show a variety of viewpoints and diversity. This collection is meant to incite and excite conversation among engineers, scientists, and society at large. It would serve as a catalyst for a three-credit course as an introductory engineering subject to non engineering university students. As university education develops to better prepare future leaders to appreciate science, technology, engineering, and mathematics, engineering courses for non engineering majors are essential and so is the requirement of worthy textbooks. This monograph intends to be one of the useful tools available. The wide range of topics includes nuclear power, small hydroelectric plants, wind turbines, and organic photovoltaics. Nanotechnology, natural gas, and deep sea oil drilling have also been presented. Energy efficiency has been called the "fifth fuel" and these topics have been covered. The four hydrocarbon fuels are oil, coal, natural gas, and biofuel.

KEYWORDS

efficiency, hydroelectricity, nanotechnology, natural gas, nuclear power, organics, solar, wind

Contents

List of Figures

List of Tables

Preface

Essays in Energy is a collection of 13 chapters by 13 seniors in the graduating class of a major American University. They all performed this research paper under my tutelage. The current topics were proposed to them, but they ultimately had the freedom to select their energy topic and design their own approach to the general topic. An overriding instruction was that the information had to be current, accurate, and cited; any new insight would be appreciated, and the presentation and writing had to be interesting. In a class of about 50, these were selected for their quality and appropriateness.

This collection is meant to stimulate discussion among engineers, scientists, and the general public. It would serve as an excellent textbook for a three-credit course as an introductory engineering subject to nonengineering undergraduates. As university education evolves to be more orientated towards science, technology, engineering, and mathematics, engineering courses for nonengineering majors are becoming more common and the need of good textbooks have emerged. This book is aimed at fulfilling this need.

The topics range from a discussion of nuclear power, small hydroelectric plants to wind turbines and organic photovoltaics. Natural gas resources in the world are examined, and so is deep sea oil drilling. Nanotechnology in the energy industry is discussed. The energy efficiency of the industrial sector, commercial sector, and agricultural sector are presented.

The honor and glory should go to the 13 authors of the chapters collected here. It is testament to their talent and knowledge, and the fine education they obtained from K-12 (from all around the country) and their alma mater. This book is dedicated to all of them and their families who supported them. May all their futures in engineering be bright and long-lasting.

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CHAPTER 1

Nuclear Power: Waste or Fuel?

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1.1 INTRODUCTION

Nuclear reactors depend on a process called fission, in which the nucleus of a particle is fragmented into smaller components either by radioactive decay or nuclear reaction. This fission process commonly generates free neutrons and photons and releases an extremely large amount of energy. In order for fission to occur, first two nuclei must interact. This will only happen if a neutron travels within the target neutron's "cross section" area, the area a neutron must travel through in order to create a reaction. This cross section is highly dependent on the speed of the neutrons, as slower neutrons have a much greater chance of interacting. Even if a neutron passes through the cross section and is captured by the target neutron, fission is not guaranteed. This cross section is the probability that a reaction will occur. Particles with an odd amount of neutrons are preferred, as it takes substantially less energy to trigger fission in them. Fission in U-235 releases an average of 2.5 free neutrons per reaction, which continue to collide with other U-235 isotopes and begin a chain reaction.

There is only one other fissionable isotope used during nuclear reactions and that isotope is P-239. This isotope can be created when a neutron collides with a U-235 isotope and is absorbed without initiating the fission process. The isotope will then become heavier and absorb additional neutrons to create U-239, in which beta decays to Np-239 and, in turn, beta decays to form P-239. This process is utilized in fast-breeder reactors where a depleted U-238 blanket is placed around the reactor core to capture neutrons, thus creating more fuel. The heavier nuclide may then absorb another neutron to become an even heavier element. These heavier atoms are known as transuranics, variously called “nuclear waste” or “spent fuel.” Since this chemical process has not yet been perfected, the creation of nuclear waste is unavoidable.

1.2 NUCLEAR WASTE

Nuclear waste is categorized into three levels: low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW). LLW is principally made up of rags, paper, clothing, filters, tools, etc., which carry slight amounts of short-lived radioactivity. LLW can be transported and handled without shielding where shallow land burial is sufficient. Since LLW contains 90 percent of the volume of nuclear waste, most of it is often compacted or incinerated before disposal. Even though LLW encompasses 90 percent of nuclear waste, it contains only 1 percent of the radioactivity of nuclear waste.

ILW contains greater quantities of radioactivity than LLW. It is comprised of resins, chemical sludge, and metal fuel cladding used to shield reactor cores. Contaminated materials from reactor decommissioning are also classified as ILW. Some ILW does require shielding when being handled and smaller items and non solids may be solidified in concrete. ILW makes up about 7 percent of the volume and covers about 4 percent of all radioactive waste.

HLW is the waste produced from the fission of nuclear fuel. It includes the fission products and transuranics produced by the reactor core. This waste is highly radioactive and very hot, leading to the requirement of cooling and shielding before handling. HLW comprises 95 percent of all radioactive waste. It can be dealt with in two distinct manners: storage and removal, or recycling. Both will be discussed in depth further in the current essay.

1.3 NUCLEAR FUEL REPROCESSING

Nuclear energy is interesting because spent fuel can be reused via reprocessing to conserve the fissile and fertile materials, providing fresh fuel for future power plants as well as existing power plants. Reprocessing allows for the recovery of uranium and plutonium from spent fuel in order to avoid the waste of such a valuable resource. Reprocessed uranium, also known as RepU, makes up about 96 percent of the fission products in which less than 1 percent is the fissile U-235 while the rest is comprised of different uranium isotopes such as U-233 (fissile), U-234, U-236, and U-238, with U-238 being the majority. The constituents of RepU are dependent on the initial enrichment and time the fuel has stayed within the reactor. Up to 1 percent of plutonium can be recovered from the spent fuel as well. However, the procedure for reprocessing the plutonium is significantly different from the reprocessing of uranium.

Commercial salvaging facilities employ a widely accepted hydrometallurgical PUREX (plutonium uranium extraction) procedure where the spent fuel is hacked, treated with concentrated nitric acid, and mined. The extracted uranium must be sent to an enrichment plant to be re-enriched due to the fact that it contains some neutron-absorbing U-234 and U-236 isotopes. On the other hand, the plutonium is sent to a conversion plant to be manufactured into mixed oxide (MOX) nuclear fuel. This is done as soon as possible due to the decay of short-lived plutonium isotopes, particularly the Pu-241 and Pu-238 with half-lives of 14 and 88 years, respectively [1, 2]. The fissile concentration of MOX fuel can be easily increased simply by adding more plutonium, leading to the burning of fuel harder and longer. This is not the case when enriching uranium, as the enrichment of uranium to higher levels of U-235 is expensive. The reprocessed fuel can then be easily recycled and used in light water reactors where the process is started once more.

To date, countries that have sided with the reprocessing of nuclear waste include Belgium, China, France, Germany, India, Japan, Russia, Switzerland, and the United Kingdom. Reprocessing of nuclear fuel does produce HLW that needs to be stored and disposed once uranium and plutonium are extracted. However, the amount of HLW needed to be stored is reduced through the reprocessing procedure. “Until the current time, about 90,000 tons (of 290,000 tons discharged) of used fuel from commercial power reactors has been reprocessed” [1]. Annual recovering capability is about 4,000 tons per year for normal oxide fuels, but not all plants are online (Figure 1.1) [1].

While reprocessing does decrease the amount of HLW that needs to be stored for decay, the United States has elected to not reprocess its nuclear waste.

> In 1977, the United States gave up on this plan for two reasons. Reduced projections of demand for nuclear power indicated no

	Use of enriched RepU	Use of Pu in MOX	Total Unat replaced
2013	1,850	1,220	3,070
2015	1,850	1,260	3,110
2020	1,880	2,140	4,020
2025	1,560	3,200	4,760
2030	1,270	3,650	4,920

Figure 1.1. Predicted savings in natural uranium requirements due to recycled U and Pu (tons) [1].

need to reprocess plutonium into new fuel for a long time to come, and it was feared that if the closed cycle were widely used, the separated plutonium could be stolen or channeled for use in nuclear weapons [2].

Plutonium inside of a reactor or recently discharged fuel is guarded by a radiation field that makes the stealing or diverting of plutonium for the use of manufacturing weapons very difficult. Reprocessing leads to the separation of plutonium from the discharged fuel resulting in the loss of the radiation barrier. Without this barrier to protect the plutonium, it would be easier for terrorists or criminals to steal. In addition, the loss of the radiation field would make it easier for a nation to divert its use to the production of nuclear weapons. It was understood that the use of weapon-grade plutonium created a considerable risk concerning the safety of any country. As proliferation worries began to arise, the Treaty of the Non-Proliferation of Nuclear Weapons (NPT) was created and opened for signature on July 1, 1968. On May 11, 1995, the treaty was extended indefinitely. A total of 190 parties have joined the treaty, including the five nuclear-weapon states [3]. The five nuclear-weapon states under the NPT include the United States, the Soviet Union, the United Kingdom, France, and China.

1.4 NUCLEAR FUEL DISPOSAL

In order to handle the HLW that is being produced by nuclear reactors, many countries have sided with the option of storing and disposing of the spent fuel created from the nuclear fission process. Most reactor sites store the spent fuel on site in reinforced concrete pools several meters deep in order for the HLW to cool and decay. The spent fuel is contained in racked fuel assemblies made of metal with neutron absorbers designed to hold all of the fuel for the life of the reactor. These fuel assemblies are packed in closed cells with air circulation and protected by a concrete enclosure. Once the fuel assemblies have been allowed to cool inside the vault for multiple years and the decaying process is well underway, they are sealed inside casks or multipurpose canisters. Each canister can hold about 80 fuel assemblies. These canisters can then be transported to a predetermined storage site. For storage, each canister is enclosed in a ventilated storage module made of concrete and steel where the canisters can be left standing on the surface or buried below the surface with the tops showing to allow cooling by air convection. The units in which the containers are placed afford full radiation shielding. However, storage such as this is only temporary until permanent storage or disposal can be found.

In order for the waste to be disposed of or stored permanently, considerations for environmental releases have to be made. A multiple barrier geological disposal procedure must be planned. There are many steps to ensure that the waste is isolated from the atmosphere. The waste is first immobilized inside an insoluble matrix such as glass or synthetic rock, then sealed inside a corrosion-resistant container, moved deep underground inside a stable rock structure, and finally surrounded with an impermeable backfill [4]. Countries such as the United States, Canada, Finland, Sweden, Spain, and South Korea all rely on a direct disposal system such as this. Currently, the United States stores all of its nuclear waste on site with plans to relocate all of the spent fuel to a central repository at Yucca Mountain in Nevada. The U.S. Senate approved of the development of the Yucca Mountain repository in 2002. However, following the 2009 presidential elections, the Obama administration attempted to abort the Yucca Mountain project, and a high-level “Blue Ribbon” commission was appointed to conceptualize alternative proposals. This delay led to $1.2 billion to be paid in utilities for the dry cask storage of HLW at nuclear sites in 2012 [5]. In order to avoid any further utilities to be paid by the Department of Energy, they announced the development of an interim storage facility to be operational by 2021 followed by a larger interim storage facility to be operational by 2025, as well as an underground disposal facility to permanently store and dispose of nuclear waste by 2048. However, this mandate did not include the option of fuel reprocessing [6, 7].

A long-standing question that is still under debate is whether or not the nuclear waste should be placed so that it is available for retrieval from the repositories. It is possible that future generations can reuse the buried waste as fuel once the spent fuel has decayed and become more stable. This would be a very valuable resource. If the fuel were available to them, the nuclear waste from decades before can be used as fuel and the energy can be conserved and continuously used. Perpetual closure of the facility would result in long-term security. After being put into the ground for about a millennium, most of the radioactivity will have decomposed. The lingering radioactivity then would be somewhat the same as that of natural uranium ore, though it could be unnaturally concentrated [8]. France, Switzerland, Canada, Japan, and the United States all require that the waste be retrievable, but it is anticipated that the depository be closed for the long term to meet safety requirements.

1.5 CONCLUSION

The creation of nuclear waste through the process of nuclear fission is unavoidable. However, the spent fuel produced can either be recycled immediately through reprocessing and storage or stored directly without additional processing and possibly used by future generations as a resource. Both processes require the storage of HLW but the amount of waste produced by both processes differs significantly. Considering the implications as to why nuclear fuel reprocessing is dangerous, the benefits of reprocessing outweigh the disadvantages. The possibility of the reprocessed plutonium being stolen can be minimized relatively easily. Hiring more security to protect the reprocessed plutonium is a simple solution to not only increase safety of transportation and handling, but provide jobs for qualified citizens as well. As far as the use of the reprocessed fuel is concerned, modifications to the nuclear reactor to accommodate the MOX fuel must be made but this process can easily fund itself once more energy from the original uranium and plutonium can be harnessed. These two substances can be renewed as fuel, equivalent to 30 percent savings on natural uranium that would have been necessary if starting from scratch. The materials hypothetically extractable for recycling (but sealed in stored used fuel) could be used to operate the U.S. reactor fleet of about 100 GWe and 30 years without fresh uranium input [6].

For immediate short-term uses, nuclear waste can only be reprocessed to create new fuel and decrease the production of HLW. On the other hand, immediate storage of spent fuel can be used as a powerful resource for future generations when considering potential long-term uses. Once decaying of the radioactive isotopes occurs and the nuclear waste reverts to its more stable U-235 state, it can be reused to power nuclear fission once again. In regard to this fact, all nuclear waste can be considered as fuel. The only drawback to storage such as this is the sheer amount of time necessary for radioactive decay to occur. Usually a period of 1,000 years is needed for the waste to become fissile once more. Furthermore, the process considering the disposal or reuse of the nuclear waste is left entirely to the country producing it.

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CHAPTER 2

Small Hydroelectric Plants

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2.1 INTRODUCTION TO HYDROPOWER

Hydroelectricity can give civilization many advantages, such as low cost of electricity, reliability, and a large storage capacity. Some hydropower plants provide not only a source of electricity but also control of flooding and irrigation systems. Hydropower holds the largest share of renewable energy generated worldwide and has generated more electricity in existence than any other renewable energy source [1–4]. Renewable energy is energy which when generated does not deplete the original source used [1–8]. The potential to expand hydropower as an energy resource remains and this potential is being explored. The International Energy Agency (IEA) has created a roadmap that foresees, "by 2050, a doubling of global capacity up to almost 2,000 GW and of global electricity generation over 7,000 TWh. Pumped storage hydropower capacities would be multiplied by a factor of 3 to 5" [5]. Both large and small hydropower projects can have an impact on society. Improving existing hydroelectric plants will also aid in the growth of reliance on hydroelectric power. When hydroelectric plants, both large and small, are developed, they must not have a large negative effect on the environment. Everything must be planned carefully in order to prevent any problems that can hurt the environment.

Hydropower is very competitive in terms of cost as compared to other renewable resources. According to the IEA, hydropower contributes "to more than 16% of electricity generation worldwide and about 85% of global renewable electricity." The improvements needed for hydroelectric power plants today are to increase efficiency and lower cost while also minimizing the negative environmental impact. Hydropower has widespread usage with "use in 159 countries. It provides 16.3% of the world's electricity (about 3 500 TWh in 2010), more than nuclear power (12.8%), much more than wind, solar, geothermal and other sources combined (3.6%), but much less than fossil fuel plants (67.2%) (IEA 2012a)" [5]. Hydropower is a focus in engineering today as it does provide more electricity worldwide than all other renewable resources combined. Hydropower still produces much less electricity than that produced by fossil fuel plants, and engineers are hard at work to make this change. In countries part of the Organization for Economic Cooperation and Development (OECD), hydropower accounts for about "13% (about 1,400 TWh in 2008). This is smaller than in non-OECD countries (19.8%, about 2,100 TWh in 2008), where it has increased by an annual average 4.8% growth rate since 1973" [5]. In Figure 2.1, the means of electricity generated worldwide from 1973 to 2010 is shown. Hydropower is a bit more reliable as compared to its counterparts, wind and solar power. This can be attributed not only to its storage capabilities but also to the fact that falling of water can be more easily predicted than that of other sources such as wind.

2.2 DIVERSITY OF HYDROPOWER PLANT DESIGN

Hydropower plants are very diverse in their design. The type of plant or the size of the plant can vary differently. This allows for large systems or also very small plants. The design will be based on parameters such as height of the water fall, known as head. The design of the plant is very much reliant on the local conditions as it is being designed to harness the mechanical energy of a river or stream and must take into account the environment in which it is built in. The roadmap of the IEA is classified into three main categories: "run-of-river (RoR), reservoir (or storage) hydropower plant, and pumped storage plants (PSP). Run-of-river and reservoir hydropower plants can be combined in cascading river systems and pumped storage plants can utilize the water storage of one or several reservoir hydropower plants" [5].

A RoR system retains energy by production of electricity created from the flow of the river. By storing water in a reservoir, a consistent

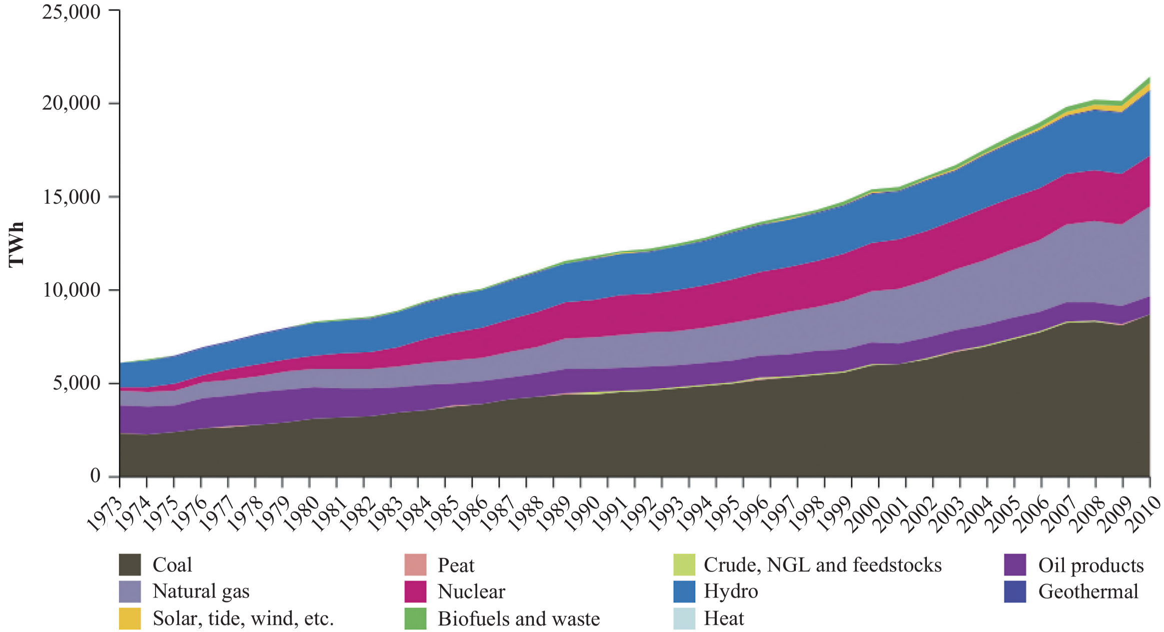

Figure 2.1. Global electricity generation by fuel, 1973–2010 [5]. NGL, natural gas liquid.
Source: Unless otherwise indicated, the material in all figures, tables, and boxes are derived from IEA data and analysis.

flow rate can be obtained that creates the required electricity on demand. The reservoir, if large enough, can also help with flood prevention and providing water for irrigation systems. In a cascading system, a large reservoir at a higher point regulates the flow over a series of smaller reservoirs downstream.

In the PSP, water is pumped from a low to a high reservoir when there is more electricity generated than needed at that time. When electricity needs to be generated, water is released through a series of turbines to generate electricity.

> Both reservoir hydropower plants and pumped storage plants store potential energy as elevated water for generating power on demand. The difference is that pumped storage plants take energy from the grid to lift the water up, then return most of it later (round-trip efficiency being 70% to 85%), so a pumped storage plant is a net consumer of electricity but provides for effective electricity storage. [5]

2.3 SMALL HYDROELECTRIC POWER PLANTS IN USE

The Czech territory has hydropower plants that they use as an energy resource. Currently,

> The Czech Republic operates approximately 1,300 SHSs with 60% of those with 100 kW maximum outputs. In the Czech Republic, approximately 3.3% of total electricity production is produced by hydropower stations which (including pumped storage) represent approximately 12% of installed capacity of Czech power stations. Most of this capacity (90% approximately) is produced on facilities with installed capacity more than 5 MW. [4]

The majority of their plants need to be upgraded and modernized in order to increase the capacity of the stations. The Czech Republic also has conditions that are good enough to construct more small hydroelectric power plants and increase the overall percentage of energy they use that is produced by hydropower. The conditions are not perfect but still sufficient for the small hydroelectric plants to be successful in energy production.

In the Czech Republic, a small hydroelectric power plant is utilized. A company by the name of CEZ Obnovitelne zdroje is a renewable resource provider that "produced 113 mil kWh of electricity in its small hydroelectric power plants in 1H 2007. It was more than during the whole 2006. This production has covered annual consumption of 32,000 households" [9]. With modernization of the current plant CEZ had in use, it was able to greatly increase the production from its small plant.

Currently in Brazil, large hydroelectric plants generate power and send electricity through a network of transmission lines. This system cannot be implemented in the Amazon rainforest as there are many scattered small towns. These small towns need only a small amount of power. Having lines that must cross rivers and run through the tropical jungle would have a very negative environmental impact and is counterproductive. The isolation of the small towns also proves to be a major dilemma as they have very limited accessibility. From these facts "faculty members of the Federal University of Para (UFPA) concluded that the best way to solve the problem would be to build isolated power plants using small rivers of the region" [10]. The benefits of this method are that these plants will have a small negative effect on the environment as opposed to applying the method used by Brazil. This method would provide energy all day long with little maintenance. The maintenance can be conducted by the people of the community. This community will then be self-sustaining and the power plant system would be quite beneficial.

2.4 DESIGN OF SMALL HYDROELECTRIC POWER PLANTS

The overall system of the small hydroelectric power plant still has room for improvement. Generally, in the industry, the turbine efficiency and cost of the system have been focused on greatly and other components of the system need to be more heavily looked at. Turbine designs and transmission technology are continuing to advance. Environmental concerns are causing change in the design of the systems as well as the operation of the plants. With consideration of the advances in technology, "the generation of electricity derived from hydroturbines has now a growing capacity of total world-wide installations of about 5% per year, doubling about every 15 years" [11]. A great feature of hydroelectric power plants is that they have a large life span as a result of continuous steady-state operation at relatively mild temperatures and mechanical stresses.

There is no clear definition of what differentiates a small hydroelectric power plant from a mini- or micro-hydroelectric power plant. In general,

> Micro hydropower schemes are usually described as those having capacities below 100 kW, mini hydropower plants as those ranging from 100 kW to 1 MW while small hydroelectric plants as those that produce electric power ranging from 1 to 30 MW. [11]

Small hydroelectric power plants have started showing a more widespread usage as a result of the benefits they provide. Countries are becoming more accepting of using hydropower as a resource: "Recent international surveys on small hydropower facilities (with capacities below 10 MW) reveal that small hydropower plants are under construction or have been already constructed in more than 100 countries" [11]. With the continued design of small hydroelectric power plants that can produce large amounts of power as compared to their size, they will continue to show up more. Hydropower could be well on its way to becoming a widely accepted alternate energy resource.

The objectives when designing the hydroelectric power plant system are mainly focused on the total annual energy output of the hydroturbine in terms of power.

> Given the type of hydroturbine and site hydrogeographical characteristics (i.e., stream duration curve parameters) and topology (i.e., available vertical fall of water) the nominal flow rate at which the hydroturbine should operate must be determined by means of optimizing appropriate techno-economic criteria under specific operational and environmental constraints. [11]

The optimal plant configuration must take into account the maximization of the investment efficiency and the maximization of the energy output produced annually.

2.5 AUTOMATIC CONTROLS IN SMALL HYDROELECTRIC PLANTS

When it comes to a small hydroelectric plant that has a power output from 1 to 30 MW with a head less than 30 ft., it is rarely economical just to have a human operator. For this purpose, automatic controls are needed. Automatic controls involve the implementation of a control theory for a system of processes that do not need human intervention [3]. The automatic hydroelectric power plant system of the Iowa Railway and Light Company at Cedar Rapids is an example of a hydroelectric plant that was able to phase out its operators in a smaller station with losing control of the plant. The station "consists of three 400-kw., 500-kv-a., 60-rev. per min., 2300-volt, vertical generating units, tied in to a system, of which the main generating station contains about 20,000 kv-a. in steam turbo-generators" [2]. With the implementation of automatic controls over the system, Iowa Railway and Light Company was able to decrease its costs substantially.

2.6 ENVIRONMENTAL IMPACT

Hydroelectric power plants have an environmental impact as with most sources of energy that can be converted into electricity. Hydroelectric systems have a noticeable presence in any landscape. Even a small "mini-hydro, e.g. 100 kW calls for some modification in stream flow, a weir at least; hence this barrier creates an up- and down-stream system. Large dams, 15 m and higher present a notable presence in the landscape" [12]. The major factor with dams is that reservoir size determines the life of the hydropower system. One of the criticisms for dams is that they are a barrier for fish and animals that live in the rivers and streams. Fish ladders and elevators can be used to help the fish along. Overall, hydroelectric power plants produce relatively clean energy when constructed and managed properly. They are much cleaner than other energy sources used in today's society.

2.7 SMALL HYDROPOWER UTILIZATION

Small hydropower plants are usually located in close proximity to the customer. Some significant features of small hydropower plants consist of the

> run-of-river type, construction in a relatively short period of time, possible subsidies on capital costs, not requiring large areas, using well developed technology with an overall efficiency of over 80%, and having automatic operating systems with low operation and maintenance costs [8].

Hydroelectric power plants are free of producing waste and do not have a large impact on the land like opencast, underground mining, and the transport of fuels do. When managed properly, hydroelectric power systems are very safe.

Depending on the storage capacity of the reservoir, fluctuations in the available water flow could be experienced. The flow is highest during the winter months and lower in the summers. Hydropower can be affected on a yearly basis by how wet a year is. Every country has a different definition of what it considers to be a small hydropower plant. The United Kingdom defines it as 5 MW, the Czech Republic as 10 MW, Sweden as 15 MW, Colombia and Australia as 20 MW, India and China as 25 MW, and Philippines and New Zealand as 50 MW. Depending on the location there can be dam-based, canal-based, or run-of-the-river systems. Some of the components in a small hydropower system are “desilters, water intakes, trash racks, and spillways. A pump house contains the turbo generator, controlling and synchronizing equipment” [4].

2.8 GENERATORS IN HYDROPOWER SYSTEMS

A couple of the common generators used in hydropower systems are induction generators and synchronous generators. The induction generator is a more affordable unit with a more reliable, simpler design. Some downsides to the induction generator are that it locks up near its synchronous rotation speed and requires an external reactive power supply to activate its magnetic field. A major difference from a synchronous generator is that it generates “its own reactive power and supports grid voltage at its point of coupling” [4]. With an induction generator sometimes the addition of external capacitors can be problematic. If the grid were to become disconnected, this could be hazardous as the generator would be feeding the capacitors directly without any regulation system.

2.9 ELECTRICITY PRODUCTION USING CURRENT WATER SUPPLY SYSTEM

In the Czech Republic, water moves in great volumes through the piping systems as it is under pressure. This is the water used by the population in their homes and buildings. Some of the companies that produce and supply the drinking water have started to utilize the movement of the water in order to generate electricity. These companies “have started building small hydroelectric plants at the entry points into the water treatment plants and water cisterns and using the hydroelectric potential of the conveyed water, both drinking and untreated" [4]. The systems used for the turbines and bearing fittings in the hydropower system are safe and will not affect the quality of the drinking water. The water then serves two purposes. In order to produce the electricity, the small hydropower system uses the water that flows from the water treatment factory to the main pipeline. The water turns turbines connected to a generator as it makes this journey. With automatic controls, the inlet flow rate of the water is monitored and adjusted. Another benefit of the small hydropower system to the drinking water is that it aerates the water as it flows through the pipes. It is even possible that "a water treatment facility with an installed small hydroelectric plant can be self-sufficient" and will sometimes even produce more power than is needed and can sell this power for a profit [4].

2.10 CONCLUSION

Small hydroelectric power plants are growing as a source of power worldwide. There are still many areas in these systems that are in need of improvement and attention. If more plants are able to be constructed, the use of hydropower will continue to grow. Modernization of existing systems will also help in the effort to produce more hydropower efficiently. With the increased use of hydropower, the environment must never be neglected. Environmental concerns will always be present, and small hydroelectric plants must be built with the environment in mind.

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CHAPTER 3

Small Wind Turbine Applications and Market Analysis

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3.1 INTRODUCTION

The purpose of this chapter is to analyze prospective market trends and general applications of small wind turbine technologies, including the possible impact of emerging technologies on the wind industry. To achieve this goal, one must first understand the extensive and enduring history of wind turbines as well as review some of the basic guiding principles to the wind turbine aerodynamic theory.

3.1.1 BACKGROUND

The implementation of wind harvesting technology, specifically windmills or wind turbines, has been around for several millennia, with the first recorded use of a vertical axis windmill occurring in Persia, around 500 to 900 BC. As this technology spread throughout Europe and the Middle East, windmills were generally used for water pumping and food production. By AD 1000, European countries, most notably the Netherlands, began refining the vertical axis design to the first horizontal axis designs, which proved to be more efficient. This is because the original vertical axis windmills lost a significant amount of collection area due to shielding requirements. Over the next five centuries, European windmills improved significantly with several innovations. The first was the ability to manually orient the rotor blades directly into the wind, which optimized energy and power outputs for a given wind speed. The second innovation was the optimization and design of windmill sails that generated aerodynamic lift, which subsequently improved rotor efficiency and improved grinding and pumping capabilities due to an increased rotor speed [1].

Beginning in the late 19th century, the first wind turbines for electricity production were designed. Over the next 60 years, from the 1890s to the 1950s, the structural efficiencies of wind turbines increased with the implementation of steel blades, and electrical power production skyrocketed with the first megawatt-rated turbine created in Vermont in 1941 [2]. Beginning in the 1970s, the National Aeronautics and Space Administration started researching commercial wind turbines, which helped pave the way for the first wind farms being established in the 1980s [3]. Since the 1980s, the wind turbine market has been composed of the small wind market, defined as having a capacity rating of 100 kW or less; the midsized market, defined as a capacity rating between 101 kW and 1 MW; and the utility market, defined as greater than 1 MW in size [4]. It is important to note the large impact of "small wind" over the past several millennia, and although recently, wind energy production has been predominately utility sized, the potential for small wind applications to return to prominence is available in the current market and will be examined later.

3.1.2 WIND TURBINE DESIGN CONCEPTS

For all three of the wind turbine markets, the guiding aerodynamic principles that define wind turbine power production are generally the same, just scaled accordingly. Depending on the topology of the turbine, the aerodynamic force that generates power is either lift- or drag-based designs [5]. Typically, lift-based horizontal axis wind turbines are the most popular topology because of good performance, minimal design constraints/difficulties, extensive research, and prolonged commercial application. Vertical axis wind turbine designs are more diverse and accompany both lift- and drag-based designs. These designs are typically less popular than horizontal axis designs because of less applied research, and the introduction of fatigue due to applied forces acting in both directions for each revolution, often resulting in failure of the turbine. However, these designs have several advantages over the horizontal axis designs, such as being omnidirectional and, therefore, not requiring an orientation mechanism; ability to be more densely arranged because of the omnidirectional attribute (i.e., no wakes that may inhibit the rotation as in horizontal axis designs); and gear boxes, brakes, and generators that can be stored close to the ground [6].

Typically, turbines of the mid- and utility-sized markets are of the conventional horizontal axis design. This is because large flexural loads introduced with increasingly larger vertical axis designs are less understood and pose more of a financial risk due to fatigue complications. However, for small wind turbines, all of the aforementioned designs are popular because proper material selection can overcome any of the minimal fatigue loads experienced in a smaller design [7]. All three designs will be considered when analyzing the small wind market and potential applications.

3.1.3 THEORY

Now that several popular topologies of wind turbines have been discussed and it has been made apparent that all of these topologies play a large role in the small wind market, some important concepts of wind turbine aerodynamics will be discussed to highlight the potential efficiencies of small wind turbines in relation to industry analysis and small wind system applications.

3.1.3.1 Lift, Drag, and Moment Coefficients

The aerodynamic force that acts on an airfoil can be decomposed into lift and drag forces, and a pitching moment [8]. The component of the aerodynamic force that is perpendicular to the incident airflow is lift and the force parallel to the airflow is defined as drag, as seen in Figure 3.1.

The lift force occurs because of an unequal pressure distribution over the top and bottom surfaces of the airfoil [10]. Additionally, the drag force occurs because of viscous forces acting on the airfoil and an adverse pressure gradient that causes flow separation and a pressure drag [10]. The following equations provide a dimensionless representation of the lift and drag forces as defined by the lift and drag coefficients.

$$C_L = \frac{L}{\left(\frac{1}{2}\right)\rho V^2 s} \tag{3.1}$$

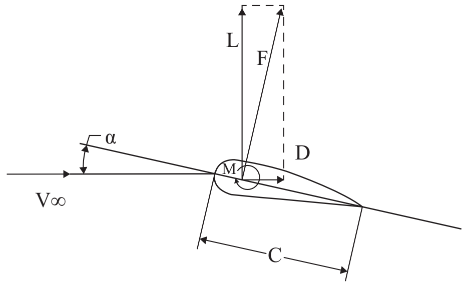

Figure 3.1. Aerodynamic forces and moments on airfoil [9].

$$C_D = \frac{D}{\left(\frac{1}{2}\right)\rho V^2 s} \tag{3.2}$$

In Equations 3.1 and 3.2, ρ is the air density, V is the free stream velocity, and S is the planform area of the airfoil. These relations are important in wind turbine design because the larger lift-to-drag ratio (of lift-based designs) will help provide an optimal production of electricity.

A useful simplification to understand is the fact that the pitching moment remains constant at the aerodynamic center for varying angles of attack. The aerodynamic center is defined as the ¼ chord location of an airfoil and is also the location where the aerodynamic forces act. The moment coefficient is defined in the following equation.

$$C_M = \frac{M}{\left(\frac{1}{2}\right)\rho V^2 Sc} \tag{3.3}$$

In this relation, c is the length of the airfoil. The moment coefficient is useful in wind turbine design because of its application to static stability such as static yaw stability.

3.1.3.2 Tip Speed Ratio

An important concept in the wind turbine design is the tip speed ratio. The tip speed ratio of a wind turbine is defined as the ratio of the rotor's tip speed in relation to the wind velocity. This concept is useful in determining the optimal rotor efficiency, in that the rotor spins fast enough to extract the maximum amount of energy from the wind but not too fast that the rotor would obstruct the wind flow [11]. The tip speed ratio is defined as follows.

$$\lambda = \frac{\omega R}{V} \tag{3.4}$$

where ω is the angular velocity of the rotor, R is the rotor radius, and V is the free stream velocity of the wind. An important design consideration is that a larger tip speed ratio improves the efficiency of the turbine but also increases noise levels [12]. Depending on the application of a small wind turbine, noise production may or may not be a significant design consideration and, therefore, may affect the maximum power coefficient that can be obtained.

3.1.3.3 Betz Limit

The maximum power that can be extracted from wind is defined as the Betz limit. Derived from the conservation of mass and momentum principles, the ideal kinetic energy that can be converted into mechanical energy is 0.593 or 59.3 percent [8]. It is important to note that this quantity has no dependence on the geometry of a wind turbine and can therefore be applied to a variety of tip speed ratios and power coefficients. As seen in Figure 3.2, the maximum power coefficient that can be obtained increases depending on the tip speed ratio. With regard to small wind turbines, this concept is important because, for a given tip speed ratio, the maximum power coefficient can be obtained and, from this, possible optimal designs for available wind, noise, and structural constraints can be chosen.

3.1.3.4 Blade Element Momentum Theory

The most widely used model for determining a wind turbine's aerodynamic performance is the blade element momentum theory. By breaking a turbine rotor blade down into smaller pieces, one can calculate the forces acting on each element. From this, the result of every element is integrated and calculated for one rotor revolution to obtain the resultant forces and moments of the turbine rotor for a variety of wind speeds, angle of attacks, pitch angle, and rotational speeds [12]. Although

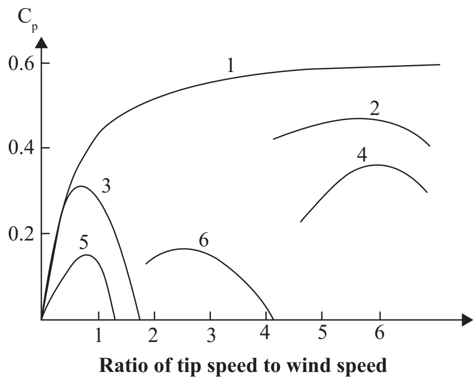

Figure 3.2. Pressure coefficient versus tip speed ratio.
Note: 1, Betz limit; 2, high-speed two blade; 3, Savonius; 4, Darius; 5, American multiblade; and 6, Dutch four blade [11].

a useful tool in determining local propeller forces, several assumptions and corrections need to be made. These include the following: each element is independent of other elements, flow is steady and nonturbulent, tip losses are not accounted for, and yaw is not accounted for. The latter two can be considered through correction factors to provide a more reliable model [13]. This model can be immensely useful in predicting rotor performance and selecting an optimal design for any of the various applications of small wind turbines.

3.2 DISCUSSION

Two important criteria to judge the success of the small wind turbine industry are to examine the potential applications where small wind turbines may be utilized and understand the market trends to determine how the industry will be able to compete with other energy sources.

3.2.1 APPLICATIONS

Possible applications for small wind turbine systems are diverse and vary significantly from that of large wind turbine systems. While large wind turbine systems are utilized almost entirely in wind farms, the adaptability of small wind turbine systems allows for possible residential, urban, and off-grid or remote sites. Becoming either partially or completely independent of an electric utility company has many benefits, and by applying small wind turbine systems to the following applications one can supplement or reduce entirely his or her dependence on a centralized electrical company.

3.2.1.1 Urban Environments

Small wind turbines that are designed and optimized for a built or urban environment have many unique characteristics. By being specifically adapted to their environment, these wind turbines can handle the wind gusts and turbulence that are experienced in an urban environment as well as overcome other unique challenges such as having low noise emissions and an aesthetic visual integration with the surroundings. Typically, many of these challenges are not suited for conventional horizontal axis wind turbines but are surprisingly applicable to vertical axis designs. Specifically, vertical axis wind turbines are capable of handling a significant amount of turbulence because of the omnidirectional characteristic and a lack of the dependence of an orientation mechanism. Additionally, electrical generators and gear boxes can be stored at a more accessible location, closer to the ground; they generally produce less noise and pose less of an inherent risk, due to their slower rotational speeds [14] and are often regarded as more artistic and creative looking. Although horizontal axis wind turbines are more efficient at converting wind energy into electrical energy, the vertical axis wind turbines are better suited to the unique constraints of an urban environment and can perform at lower heights than a horizontal axis design would require. Undoubtedly, small wind turbines in an urban environment are outperformed by larger turbines in typical wind farms, but small wind turbines have significant room for cost reduction and efficiency improvements [15].

Several optimal locations are available for placing small wind turbines in urban environments. The first is on the roof of buildings. This utilizes the wind stream above a structure and the building's height as advantages. Since wind speed is proportional to the cubed height of a turbine, by placing the turbine on the roof of a structure, the building's height is essentially used as an extended mast of the turbine. Important considerations with placing a small wind turbine on top of a building are that turbulent airflow may affect the turbine performance and the wind stream direction flows in an upward direction around the leading edge of the building [16].

Due to the complications of an upward flowing wind stream, a horizontal axis design experiences decreased efficiency, while a vertical axis design is capable of an aerodynamic efficiency close to 40 percent [16]. This is because a horizontal axis design performs best when the free stream velocity is perpendicular to the rotor blades. Additionally, above the turbulent layer over a building, the wind velocity increases by as much as 20 to 40 percent compared to the unperturbed wind velocity before the building. This benefit allows for additional efficiency of the turbine at the expense of additional costs of a taller turbine [16]. The other optimal location for small urban wind turbines is between buildings or in a location where wind flow area is reduced, and the fluid velocity increases. This phenomenon can help increase the energy extracted from wind by placing a turbine in a location where wind velocity naturally increases.

Wind turbine systems in urban environments have gained popularity in recent years most notably with the proposed designs of the World Trade Centre (WTC) in Bahrain and the Freedom Tower in New York City. Although the WTC in Bahrain incorporates three 225-kW turbines, the notion that similar designs utilizing small wind turbine systems could be on the horizon. One proposed design of the Freedom Tower in New York City has investigated using at least 30 100-kW small wind turbines in an effort to reduce vibration and noise, rather than fewer larger turbines [16]. This design aims to generate 2.6 million kWh annually, or 20 percent of the building's estimated energy needs. Undoubtedly, this is a great step toward producing electricity in urban environments and the possible application of small wind turbines to a growing renewable industry.

While small wind turbines in urban areas have many unique challenges and are not as efficient as larger utility turbines, a proper design, such as a horizontal axis wind turbine, for the prospective location may allow for a competitive method of electricity production to supplement one's current electrical consumption. Conversely, these challenges as well as safety considerations may be too significant and may outweigh the benefits of small wind turbines in urban environments.

3.2.1.2 Residential

There are several important considerations to take into account before deciding if a residential small wind turbine system is optimal. These include researching the wind statistics at the site, possible zoning requirements or restrictions, and estimating the economics of installing the small wind turbine system [17]. The first is obvious for installing a wind turbine and will help determine if the site is windy enough for a wind turbine to generate any energy at all and what the optimal-sized turbine is for one's location and given wind characteristics. The second is necessary to determine what permits and legal bureaucracy one must go through before being able to install a turbine. The last helps one determine if it will be cost-effective to install the turbine and if any incentives and tax breaks are available that may ease the initial investment of a small wind turbine system.

In general, a grid-connected system is useful because it not only supplements the cost of energy consumption through the grid, but also provides a backup if one's turbine does not generate the estimated or required energy. Alternatively, many utility companies offer net-metering, which allows one to sell excess electricity back to the utility company by feeding it into the grid [17]. All of these options make a residential small wind turbine system favorable as long as the wind resource in the area makes the payback period and economics of the wind turbine effective. It is also important to note that grid-connected turbine systems do not require battery storage, and therefore have high efficiencies for electrical energy production [18]. In most cases, a grid-connected small wind turbine system is most optimal if one's average annual wind speed averages 10 mph, the utility electrical cost is expensive, and the cost for connecting to the grid is not expensive. If these options are not available, it may be more effective to research other grid-connected renewable systems to reduce one's dependence on the grid.

3.2.1.3 Off-Grid or Remote Site Power Generation

Many of the qualities of residential small wind turbine applications are applicable to off-grid or remote sites with the exception that the energy generation system is intended to act as a stand-alone system rather than supplement energy consumption through an existing electrical grid. Off-grid or remote site turbine systems provide opportunities to perform as stand-alone systems and small wind turbines in remote areas can work independently or as a subsystem of a larger renewable energy system. Depending on the situation, small wind turbine systems at remote sites may be more cost-effective and economical than paying to extend to the grid or attach to an existing electrical grid. Additionally, a small wind turbine system has several other possible applications besides just electrical power generation, similar to examples discussed in the extensive history of windmills and wind turbines, such as water pumping, which may be useful in a remote location. Such applications have been implemented for hundreds of years on farms across the United States.

Similar to a residential small wind turbine system, one needs to determine if the system will be a viable option for electricity generation, as opposed to using a traditional electric company. In the case of an off-grid system, this decision may be easier to determine because, if a grid connection is currently unavailable, running an electrical line to a remote site may cost as much as $15,000 to $50,000 per mile depending on the terrain [17]. This cost alone may make it worthwhile to invest in a stand-alone system, not to mention the intrinsic benefits of generating clean power through renewable means. In most cases, it is difficult to generate enough electricity solely through a wind turbine system or it is comforting to have backup power generation capabilities. Here, it is optimal to attempt to reduce one's power consumption as well as invest in supplementary power generation technologies such as hydropower or photovoltaic panels for implementation in a hybrid energy system.

One of the most promising applications of small wind turbine systems integrated in a hybrid electrical system is in the electrification of remote areas of underdeveloped countries and isolated villages. In these locations, independent small wind turbine systems in hybrid electrical systems are optimal because these areas have low demand for power. Additionally, with no utility grid in place, these rural areas do not have other options to easily obtain electricity, which is often the main factor inhibiting development of the area [19]. Unfortunately, such rural electrification is a complex issue spanning technological, social, ecological, and economical factors [20].

In Brent and Rogers's study [20], the complex interactions between these factors determined that the implementation of such a renewable energy system was unsustainable. It was concluded that while the uncertainty in the return of productivity and the poverty reduction did not meet the standards set forth by the South African government, a unified electric grid was required in order to achieve sustainability. However, a contrasting study found success in an integrated renewable energy system located in several rural villages in India [19]. In this study, Kanase-Patil *et al.* analyzed the availability of several sustainable resources such as wind, biomass, biogas, and solar energy to determine the most reliable and cost-effective method of electricity generation. Undoubtedly, these two case studies emphasize the complexity of implementing such hybrid electrical systems in underdeveloped countries where it may not be optimal in a certain location, but the potential in another location may be significant.

It is important to note that the main disadvantage of an off-grid power generation system is that a battery and a charge controller are required to store the generated electricity. In turn, this adds additional costs to the initial investment and reduces the efficiency of the off-grid power system.

3.2.2 MARKET ANALYSIS

In order to analyze the small wind industry, one must investigate current and potential market trends of both the United States and countries abroad. For the purposes of this report, a small wind turbine was defined as being 100 kW and smaller, as defined by the American Wind Energy Association. Even though some international standards define small wind as having less than 200 $ft.^2$ of swept rotor area, which is about 50 kW, the majority of countries define the upper limit of small wind close to the 100-kW rating [21].

3.2.2.1 Cost

One of the largest inhibiting factors of the growth of the small wind industry is the incurred costs. Depending on numerous factors such as tower height, turbine type, turbine manufacturer, permitting, and maintenance costs, the cost of a small wind turbine may vary significantly. An estimation of the average cost of small wind turbines in the United States in 2012 is $6,510/kW for new and $4,080/kW for refurbished ones. A startling comparison is that midsized turbines averaged $2,810/kW and utility-sized turbines averaged $2,540/kW [22]. This disparity is due in part to the high manufacturing costs associated with the growing industry and difficult legal policies. Even if fossil fuel prices increase substantially, small wind turbines would have difficulty competing with other renewable energy sources unless technology drives cost down and policies are enacted so that permitting is less restrictive and cheaper, certification and quality are more of a streamlined process, and more economic incentives help jump-start the industry [21].

3.2.2.2 Policies and Incentives

Available incentives and policies for small wind turbines in the United States include rebates, tax credits, grants, net-metering, and loan funds [23]. All of these encourage the growth of the industry with competing interests in other renewable energies and in the shadow of fossil fuel-generated electricity. According to the U.S. Department of Energy [17], in 2013, the total amount of awards was close to $15.4 million. This number was down significantly from 2012 from more than $100 million because of the expiration of section 1603 payments, a form of treasury cash grant for turbines that were constructed by the end of 2011 [24]. In addition to important incentives like section 1603 expiring, uneven state incentives inhibit the growth of the small wind market in the United States. In numerous states, a disproportionate amount of incentive funding is provided more to solar projects than to wind projects. An example of this is seen in Massachusetts, where, in 2013, $12.9 million was provided for wind projects totaling 55 MW, while $5.7 million was provided for solar projects totaling only 15 MW [23]. Until these imbalances are adjusted, the small wind market in the United States will struggle with regard to other renewable markets.

In addition to many of the incentives and policies that are available for small wind turbines in the United States, foreign countries have found success in implementing feed-in-tariffs, where owners of renewable energy systems are paid for selling generated electricity back into the grid. These tariffs have helped accelerate demand in these foreign markets [23].

3.2.2.3 Current Statistics

According to the U.S. Department of Energy [24], nearly 72,000 small wind turbines were put in service through 2003 to 2013, totaling 842 MW. For just 2013, 30.4 MW were deployed from 2,700 new units. Although this value is significantly less than that in 2012 due to the expiration of the 1603 payment incentive, the number of installed small wind turbines was still five times greater than the number of wind turbines with a rating greater than 100 kW. While a majority of power is generated from the utility- and midsized turbines, the fact that small wind turbines jumped from 40 to 80 percent of total turbine units deployed from 2012 to 2013 shows that small wind grew in relation to the rest of the wind industry.

Of the 32 small wind turbine companies with sales in the United States, there were 74 models available worldwide and a total of $363 million in sales was recorded. These companies also reported that turbines rated below 1 kW composed of 24 percent, models rated between 1 and 10 kW composed of 46 percent, and 11 to 100 kW composed of 30 percent of all models [22]. This distribution has recently been changing, with an increase in average global wind turbine sizes from 0.66 kW in 2010 to

0.84 kW in 2012 [21]. This can be attributed to the feed-in-tariffs that make it more economical to design a wind turbine close to the upper limit of financial reimbursement through the tariff, which many countries and states have set at 100 kW.

As of 2013, the total distribution of small wind turbine global capacity was as follows: China with 39 percent, the United States with 31 percent, and the United Kingdom with 9.4 percent, and all three accounted for nearly 80 percent of all small wind turbine installations. Worldwide, the total cumulative capacity in 2012 was 678 MW, with an increase of nearly 18 percent from 2011 [21]. Overall, the small wind industry has demonstrated remarkable growth by an introduction of 120 new manufacturers in the past decade. More notable is the fact that these manufacturers come mainly from United States, Canada, China, United Kingdom, and Germany, with very little influence in other countries, suggesting a possibility of a substantial increase worldwide, should consumer demand increase.

In recent years, the number of vertical axis designs has increased significantly but still remains a small sector of the small wind industry. It is important to note that out of small vertical axis designs, the average capacity was 7.4 kW while the average for small horizontal axis designs was only 1.6 kW [21]. This disparity, along with the increase in average global wind turbine sizes, emphasizes the fact that the vertical axis market has increased substantially over recent years and may be competitive with traditional horizontal axis designs in several years.

3.2.2.4 Future Outlook

As discussed previously, for the small wind industry to sustain a robust growth in future years, many factors such as high manufacturing costs, difficult legal policies, lack of incentives, and low consumer awareness and interest need to improve. With these improvements, costs will be driven down, small wind turbines will become more reliable, and more investors and consumers will express interest in the industry. While 2013 was a difficult year for the small wind industry due to the expiration of the 1603 incentive program, the entire renewable energy market is expected to grow steadily in the next several years. Already 130 MW of small wind capacity is expected in 2014, which is significantly larger than the largest yearly increase on record of 100 MW in 2012 [23]. In terms of prospective growth in the discussed applications of small wind turbine systems, there has been a general trend toward grid-tied systems due to the introduction of net-metering and substantial growth in industrialized countries such as Denmark, the United States, and the United Kingdom [21]. However, there is still a possibility of growth in off-grid applications as 2.4 million homes lack electricity in China and already 97 percent of the small wind market is off-grid based [21]. In addition, the introduction of urban wind turbine systems is a relatively novel idea that has just recently gained traction with the proposed implementation on the WTC in Bahrain and the Freedom Tower in New York. If more urban areas begin introducing renewable designs, the small wind market could grow substantially.

3.3 CONCLUSION

The purpose of this chapter was to analyze the applications and market trends of small wind turbines, as characterized by a rated capacity less than or equal to 100 kW. This was achieved by first discussing the extensive history of wind turbines and windmills, various designs of modern wind turbines, and the aerodynamic concepts behind these designs. All of this helped provide an understanding of the breadth that the small wind turbine industry encompasses and highlight possible aspects that may influence the applications and market trends of small wind turbines.

The three main applications examined for the small wind industry were urban, residential, and off-grid or remote sites. Many considerations must be accounted for in the implementation of a small wind turbine system in all three of these applications to optimize power generation, reduce noise and vibrations, and ensure that wind energy will be a viable method of meeting or supplementing one's energy requirements. It was examined that all of these applications have a significant possibility of growth, whether as an independent power generation system or as a hybrid electrical system that utilizes any combination of solar, wind, biomass, or other renewable energy technologies.

From extensive research to actually implementing the proper topology for one's given wind characteristics and noise constraints, it is important to note the vast complexity of designing a small wind turbine system. This complexity alone is enough to restrain the small wind industry from growing rapidly, not to mention many other obstacles such as high manufacturing costs, lacking or expiring incentives, and difficult policies that also inhibit the growth of the industry. However, many promising details nuance a potential growth in the industry over the next several years. The global small wind capacity has been increasing steadily over the past decade and makes up a significant amount of the entire wind industry with as many as 80 percent of total units being below a 100-kW rating. Additionally, measures such as feed-in-tariffs have been steadily increasing the average size of global small wind turbines as well as increasing consumer interest in selling electricity back to utility companies through net-metering. The most promising aspect of the growth of the small wind market is that only five countries make up over 80 percent of global manufacturers, which leaves enormous room for growth around the rest of the world.

If many of these promising factors remain and countries encourage equal incentives for renewable energy systems as well as develop standards of quality and safety, the small wind industry will have a promising future. Until then, small wind will be shadowed by other renewable energy sources and fossil fuels. Undoubtedly though, the long-term advantages of investing in small wind and other renewable energy sources should be a priority for the United States and countries around the globe because they are clean, sustainable, renewable, and domestic sources of energy that reduce our dependence and impact on the earth. If proper steps are taken by governments and investments are made in the numerous available applications, small wind can help lead a revolution toward a sustainable society that benefits our climate, public health, and economy.

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CHAPTER 4

ORGANIC PHOTOVOLTAICS

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4.1 INTRODUCTION

Organic photovoltaic (OPVs) solar cells have the potential to revolutionize the solar energy market. For a number of reasons, the potential that exists in organic solar cells is great enough to warrant a prediction that solar energy will become as important and lucrative as any form of alternative energy, including wind and water. Although there are still numerous drawbacks and a lot of research still needs to be done, the advantages of organic solar cells over the more standard inorganic, silicon-based cells are enough to get excited about.

Before jumping into the technicalities of how solar energy is produced and what exactly is being researched to advance the plausibility of OPVs, a simple comparison with its counterpart, inorganic solar cells, can be done to broadly analyze the industry. Large-scale commercialization of solar energy depends on three criteria in particular: efficiency, lifetime, and cost. The most important advantages of OPVs are the significantly lower manufacturing costs, low weight, flexible design, continuous manufacturing process, low environmental impact, short energy payback time, and an affinity for chemical modification and specialization based on application. Clearly, there are plenty of reasons for optimism and just as abundant are the ways that OPVs can be improved. Substantial research still needs to be done to improve the cost-effectiveness of OPVs since at this point in time, inorganic photovoltaics (PVs), most commonly comprised of silicon, are still the better option. This is due to the two key advantages that silicon-based cells still have, which are efficiency and lifetime.

4.2 STATUS AND PERSPECTIVES

Solar energy is one of the big three sources of clean, renewable energy, along with wind and water. Commonly referred to as wind, water, and solar, these alternatives to oil make up around 20 percent of the world's supply of energy production. Solar energy is produced by means of the PV effect, which uses the photons emitted from the sun to excite electrons, which produces a direct current.

The solar cells that are most commonly used today are comprised of silicon. This is because silicon is a semiconductor, which means that it has properties of both a conductor and an insulator, which is a very important property. Silicon-based solar cells produce electricity because of the photoelectric effect, which is the ability of matter to emit electrons when a light is shone on it. To summarize the process, light strikes the cell in the form of photons and only a portion of them are absorbed by the semiconductor material. The energy of the photons knocks electrons of the silicon atoms loose, which allows them to move freely. With the guidance of an electric field, the electrons move in a structured direction, which in effect is the current. Then, with the use of metal contacts on the top and bottom of the PV cell, the current can be drawn off and used externally.

This is a general explanation of the process that occurs in a solar cell. In reality, there is a lot more going on. The more intricate and technical aspect is in relation to the channeling of the electrons into an electric current. As mentioned, an electrical field is used to guide the electrons. However, this electric field is created in large part due to the internal organization of silicon. Atoms of silicon are arranged in a tightly bound structure but by squeezing small quantities of other elements into this structure, two different types of silicon are created: N-type and P-type. The N-type has spare electrons and the P-type has missing electrons, which is more commonly referred to as having holes. When these two materials are placed side by side, they create an electric field. The free electrons on the N-side fill the holes on the P-side and eventually an equilibrium is reached and an electric field separates the two sides [1].

OPVs work slightly differently because of their properties, most notably, a much larger exciton binding energy. For a silicon cell, the exciton binding energy is so small that the electrons and holes can separate and, thus, a current can be produced. However, in an organic material, the strongly bound exciton does not lend itself to such easy dissociation, which is what is needed to produce a current.

In order to dissociate the excitons, organic cells are structured to include a component that corresponds to an electron donor and one that corresponds to an electron acceptor. The interface between these two components is the location of the dissociation of the excitons. However, the location of this interface is critical to the efficiency of OPVs because of the migration of the excitons. The excitons are generated where the photons are absorbed on the cell. Then, the excitons must diffuse to the interface of the acceptors and donors, or else no current will be generated. Therefore, in order to reduce the distance between where the exciton is generated and the interface, thinner films are used. However, if the film is too thin, then the number of photons that can be absorbed is limited. Hence, a perfect median between thick and thin is strived for by the engineer.

Moving forward in the process, when the exciton reaches the acceptor–donor interface, it needs to dissociate. How this normally happens is based on the fact that the light is usually absorbed in the donor material and then diffuses toward the acceptor, which is strongly electronegative. In order to initiate a charge transfer from the donor to the acceptor material, the energy difference between the electron level of the donor and the acceptor has to be larger than the exciton binding energy. This charge transfer happens very efficiently and very rapidly, as fast as 100 fps. When the dissociation occurs, the electron is transferred to the acceptor molecule and the hole remains on the polymer. This process can be visualized in Figure 4.1.

Although at this point the electrons and the holes are on two separate materials, they are still attracted to each other and can be considered to be in a charge transfer state. However, to generate an electrical current,

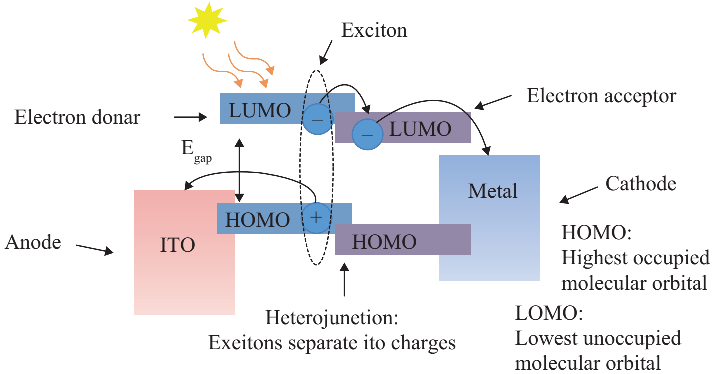

Figure 4.1. Photovoltaic effect in OPVs [1].

a full separation of the electrons and holes must occur, which is known as the charge-separated state. Therefore, as noted in the charge transfer state, there is still an attraction because of the relative proximity of the electrons and holes. This is a large source of inefficiency because of the chance that recombination may occur. If that happens, the pair will return to the ground state and light will be emitted from the solar cell, which is very undesirable.

The final step is to move from the charge transfer state to the charge-separated state. In effect, energy must be applied for this separation to occur, but there are many other factors that affect this movement. For the electrons and holes to move efficiently toward the electrodes, the material must be very ordered. Quite simply, the faster they can move away from each other, which is accomplished easily without a random, disorganized structure, the more efficient the separation will be. This is one reason why inorganic solar cells can be very efficient. Silicon can be produced with a very rigid and organized structure, which allows for rapid dissociation and migration throughout the cell.

Now that the PV effect has been explained, more of a comparison between silicon-based solar cells and OPVs can be made. As previously stated in the introduction, the three most important factors in large-scale commercialization of solar energy are cost, lifetime, and efficiency. As of now, silicon cells cost more but are much more efficient and are much more durable. Therefore, it is no surprise that inorganic options are still the preferred method of choice in the industry. With that said, since the cost of OPVs has the potential to be far less than that of any inorganic alternative, there is an extraordinary amount of research being done to further improve the efficiency and lifetime of OPVs.

The cost advantage that is associated with OPVs is in large part due to the manufacturing and processing of the material. Because of the properties of the polymers that make up the organic cells, including low-weight, thin, flexible, there are numerous processing techniques that are available for mass production. The ideal manufacturing process of OPVs should involve solution processing of all layers on flexible substrates by the combination of as few coating and printing steps as possible. It should also be free from costly indium, toxic solvents, and chemicals, and the final product should have a low environmental impact and a high degree of recyclability.

For some perspective, the production of OPVs using industrial screen printing has demonstrated the possibility of producing in the order of 1,000 to 100,000 m^2 on a process line per day, while production of the same solar cell area based on silicon typically takes one year [2]. The possibility of roll-to-roll (R2R) processing makes the enormous scale of production possible. Utilizing the flexible properties of OPVs, R2R processing is measured on a scale of seconds, whereas a comparable rigid, glass design would be measured on a scale of days. R2R processing is a broad description of processes that usually fall under coating or printing. Coating or printing refers to the different ways of producing the solar cell onto a substrate material. To summarize, R2R processing involves a substrate in the form of a very long sheet that is wound on a roll. The substrate material in this case is often referred to as the web and it is required to have some mechanical flexibility. During printing and coating, the web material is unwound from the roll and passed through the printing or coating machine and once through the process the material is rewound on a roll. Furthermore, some printing techniques are gravure printing, flexographic printing, screen printing, and rotary screen printing. In addition, the two most common coating techniques are knife coating and slot die coating [3]. Although R2R processing is the most rapid and cheap way to produce an enormous amount of OPVs, it is still in the development stages of commercialization because of the low efficiency associated with it. R2R processing is still only producing solar cells with less than 4 percent efficiency [3].

The reason that there is such a cost advantage for OPVs is mostly due to the expensive nature of silicon-based solar cells. The process of producing these inorganic cells can be briefly described in a few steps, each of which takes time and energy, which is money, for purification purposes. Highly pure polysilicon suitable for solar cells is typically produced in three steps. First, metallurgical-grade silicon (MG-Si) is obtained at around 98 percent purity from a seller. It is usually purchased because of the very small portion of the market of which solar applications is a part. Next, MG-Si reacts with Hydrochloric Acid (HCl) to form a range of chlorosilanes, including trichlorosilane, and after further purification and manipulation, it is necessary to produce thin wafers of silicon. The most widely used wafering process consists of melting and resolidifying pure silicon. These are the basis for the solar cells [4].

As for the materials used in OPVs, there is an outrageous amount of different combinations that are used for various reasons. One of the reasons why OPVs is such a promising field is because of the affinity for chemical modification, which leads to specialized materials based on a specific purpose. Of the not-so-specialized materials, by far the most successful of them are the polymer–fullerene solar cells that comprise a mixture of the polymer, which exclusively is the donor material and typically a soluble fullerene derivative as the acceptor material [5]. As stated elsewhere previously, organic solar cells can be manufactured to a thickness that is a thousandth of that of silicon solar cells; this results in significant savings on material costs.

In addition, research is being carried out to better or to substitute the two electrodes with a more suitable material. One example is carbon. In either its form of graphene or as carbon nanowires, manufacturing costs could be reduced even further, which is yet another example of why, with continued research and funding, OPVs are moving toward widespread commercialization [1].

An important factor in estimating the cost of solar cells is the lifetime of the unit. Although it may be cheaper to manufacture OPVs, they are still much less stable and durable. If one were to calculate the amount of time that OPVs needed to be fixed or replaced, there would surely be less of a gap between OPVs and silicon-based cells when looking at the big picture. Therefore, when determining which type is more cost-effective, inorganic cells are still more favorable. This is mostly due to the degradation that occurs due to the nature of OPVs. The fact that OPVs are made from molecules of polymers is very important when examining the durability of these cells. Molecules are not as stable and, in fact, will react with other molecules such as oxygen and water. As one could infer, any reactions that are taking place are not preferable. These reactions may lead to the cells not absorbing as much light, generating fewer chargers, or even trapping charges and preventing them from being collected. It is unfortunate, but true, that molecules are more likely to degrade while being illuminated. Thus, the lifetime of only around five years is troubling for OPVs [1].

This is especially true when considering that silicon-type cells have lifespans of around 20 to 25 years. Although they will lose some efficiency if they are still active after that long, they are still much more durable and dependable. This is mostly an effect of the process by which they are created. Since so much time is taken for purifying the material and it is made from atoms instead of molecules, it will generally last much longer.

Two experiments dealing with the degradation of OPVs under long exposures of light were conducted to examine the effects that various natural elements had on the efficiency. The first experiment was performed, in 2006 at the Osaka University in Japan, on two different structures, a p–n heterojunction cell and a p–i–n junction cell. A long-term operation was performed under various environments, including air, oxygen, nitrogen, and low- and high-vacuum scenarios. Also, a halogen lamp (100 mW/cm^2) was continuously irradiated under short-circuit conditions. During the process, short-circuit photocurrent and current–voltage values were monitored. The results they received were consistent with the previously stated theory. For both types of OPVs in air, there was a rapid decrease in photocurrent density. Additionally, the cells were tested in pure oxygen and a similar result was found. Thus, it was concluded that the migration of oxygen molecules from air into the organic films caused the decrease. This was accomplished because the oxygen acts as an electron trap in organic semiconductor films and prevents electron transport. However, this initial decrease in photocurrent was effectively suppressed under the high vacuum and nitrogen environments. Although a slight long-term degradation was still observed, it was only 15 percent even under 260 hours of prolonged irradiation. A conclusion was made that, for practical applications, encapsulation of OPVs should be necessary [6].

In the second experiment, the stability of encapsulated indium-tin-oxide (ITO)-free bulk heterojunction organic solar cells was tested. The cell, or rather the photoactive layer (PAL), consisted of poly(3-hexylthiophene) as a donor and (6,6)-phenyl-C60 butyric acid methyl ester as an acceptor. The cell was tested under continuous illumination (1000 W/m^2) with two trials, one with low UV content and one with high UV content. The cell showed remarkable stability with the low UV content and showed significant degradation under the high UV radiation. The degradation was characterized by a reduction in short-circuit current density and fill factor. In addition, a decrease of the effective charge carrier mobility of the PAL was found. It was concluded that the deterioration of OPVs under UV exposure was due to an increase of the sheet resistance of the polymeric hole contact. In addition, it was suggested that in order to guard against this effect, a UV-filter device would be an effective resistance to degradation [7].

Finally, the most important, most researched, most noteworthy number when dealing with PV solar cells is the efficiency. The overall efficiency is a combination of several independent efficiencies, including reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency, and conductive efficiency. At this point, it is readily apparent that silicon-based PV cells will pretty much always be more efficient than OPVs. As of now, silicon-based solar cells are being produced at record highs of around 25 percent. In contrast, OPVs are still below 10 percent and the average is closer to 5 percent than it is to 10 percent. Many sources agree that for organic solar cells to finally hit the mainstream market, a consistent figure of 10 percent efficiency and a 10-year lifespan must be reached. Although this figure is still not exactly in arm's reach yet, there is serious progress being made in a bunch of different areas. All the research being done is aiming to increase this efficiency just a little bit higher, and eventually, step by step, the goal will be achieved.

To quickly overview as to why inorganic PV cells are inherently more efficient, it is mostly related to the structure and properties of the material. First and foremost, the rigid, grid-like structure of atoms that exists is essential to the free movement of electrons. Due to the lengthy purification process and controlled manufacturing of the silicon material, the atomic structure can be manipulated to fit the specification perfectly. This is one of the main drawbacks of OPVs. Once excitons and electrons are in a rush to move, they encounter a lot of resistance because of the disorganized structure. In addition, the low charge mobilities are a big obstacle to overcome. This leads to recombination effects and lost charges, which dramatically lower the efficiency [8]. Just as important is the low exciton binding energy that exists in the silicon-based solar cells. This is the energy that it takes for the exciton to dissociate into an electron and a hole, which is vital in the formation of a current. This energy is much lower in the inorganic cell and is even easily overcome at room temperature. However, this is just about the opposite in OPVs, which need help from the heterojunction to dissociate the exciton.

4.3 DISCUSSION AND CONCLUSION

The OPVs industry today is still greatly improving. There is yet a tremendous amount of research and progress taking place to raise the efficiency of OPVs. In fact, although the average OPV is around 5 percent, there are numerous designs and test cells that have shown over 10 percent efficiency. As mentioned a few times previously, one of the greatest aspects of OPVs is the affinity for chemical modification. This means that the possibilities of research are just about endless. Polymers can be created to address any need that researchers see fit, such as polymer materials that have small band gap and high absorption range.

Researchers are trying all types of methods to increase efficiency. Another project included the use of a tandem structure with a high-performance, low band gap polymer because a broader part of the spectrum of solar radiation is used and the thermalization loss of photon energy is minimized. In the past, the lack of high-performance, low band gap polymers was the major limiting factor and because of this change, an efficiency of 10 percent was achieved [9]. Another new development is the testing of inverted OPVs, which uses the ITO covered with a functional buffer layer as the cathode. Just as it sounds, it is pretty much just flipped so that the light is absorbed on the opposite side as normal. The inverted structure has the advantage of improved stability by replacing the low work function metal cathode, which is detrimental to the device lifetime [10]. Although this technique lowers the efficiency of the cell, its lifetime is dramatically increased.

As it stands today, solar energy may be the third best option for renewable energy, but this might not be the case for long. OPVs may hold the key to change the way solar energy is looked at in the future. With enough sustained research and enthusiasm, OPVs will eventually be a very competitive alternative to not only inorganic solar cells, but to wind and water energy alternatives as well. The fascinating aspect about OPVs is the possibility to manipulate the material into any desired design, for any specific application. Because the cost is so cheap, and the material is flexible enough to be rolled, and can be printed in mass production, there will come a time when OPVs become an essential part of daily life. However, that time is not now. There is still much research needed to be done to improve the efficiency and lifetime of the OPVs in order for them to be a viable alternative to their inorganic counterparts.

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CHAPTER 5

Increasing Diversity of Renewable Energy Through Tidal Water Power

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5.1 INTRODUCTION

Both in the United States and abroad, there is ever-growing interest in the use of renewable energy sources for large-scale power generation. There are various motivations for this growing interest: concern over dwindling supplies of more traditional fossil fuels, the security of the sources of those more traditional energy sources, and concern over the effect of those fuels on the environment. Global climate change, though still hotly debated in political circles, is widely accepted in the scientific community.

One major source of global climate change is the burning of nonrenewable fuels for power generation. Nonrenewable energy sources consist primarily of coal, oil, and natural gas, the so-called fossil fuels. They are limited in their supply as they are created by geological processes over millions of years and are being consumed at a much faster rate than they can be replenished. The burning of these fuels creates greenhouse gases that are a major cause of global climate change. Currently, these fuels are the primary means of large-scale commercial power generation in almost every country on Earth. The only exceptions to this rule are those countries, such as France and Japan, that make extensive use of nuclear power.

Nuclear power is also a nonrenewable energy source, but it is considerably more efficient with its fuel, uranium. Nuclear power also generates a greenhouse gas, water vapor, as a byproduct, but this is generally considered less harmful to the environment than other triatomic gases released as a result of energy production. As a consequence, many have advocated for increased use of nuclear power in the interim, while less mature energy sources are developed [1]. The need for interim sources of power arises from the dual need to address global climate change and to sustain the power requirements of a rapidly growing human civilization. Human energy consumption is growing year by year and estimates by the U.S. Department of Energy show no change to that growth in the near future [2].

There are, therefore, many reasons for the rising global interest in renewable energy resources. Renewable energy sources are considerably broader than nonrenewable sources, but they include wind, water, and solar power as well as geothermal power. Within each of these categories, there are further subclasses. For example, solar power can be divided into solar thermal power, which uses concentrated sunlight to heat a fluid that turns the turbines, and photovoltaic power, which uses photons to generate a current. The methods for extracting power from most renewable resources have yet to reach the kind of standardization that can be seen in coal-, oil-, or natural gas-burning power plants.

Water power has even more subdivisions than solar power. The most common form of water power is actually one of the oldest forms of power generation in the world: using the potential energy of a source of flowing water, like a river, to turn a turbine. Historians believe that the first water wheel was developed some time in the third century BCE [3]. The sophistication of the devices used to harness the potential energy of flowing water has evolved, but the core principles remain the same. Modern hydroelectric plants use the flow of rivers through dams to power series of turbines to generate electricity.

Many cities and countries rely on the use of hydroelectric power. Brazil, for example, generates almost 70 percent of its electrical power through hydroelectric sources, but not without cost to the large forests upstream of the rivers that are flooded after the construction of the dams [4]. There are environmental concerns over preservation of the Amazon rainforest in conflict with environmental concerns over the polluting sources of energy generation.

In the interest of combating global climate change, a wide variety of research has and is being conducted on new sources of renewable energy. There are many challenges involved in harnessing renewable energy resources. This chapter will attempt to discuss in detail one of these suggested renewable sources, tidal water power; its application; and its potential effect on shifting human energy consumption away from nonrenewable sources of power.

Tides are periodic variations in the earth's water levels generated by gravitational shifts caused by the movement of celestial bodies, primarily the moon. The highly periodic nature of the motion of the moon, the earth, and the sun make variation in tides highly predictable. Unlike wind and solar power therefore, which are much more dependent on shifting, hard to forecast weather patterns, tidal power is very consistent. This consistency is considered a large advantage in power generation. Tidal energy is the only form of power generation that stems from the energy of the orbits and gravity of celestial bodies in the solar system. Most forms of renewable energy, particularly solar and wind, draw their energy from the sun in one way or another.

5.2 TYPES OF TIDAL WATER POWER GENERATION

Tidal water power has not seen wide use for electrical power generation, but there are several small tidal power generation stations around the world. Countries like South Korea, China, and Malaysia have plans to build large tidal power stations as part of their efforts to reduce their dependence on fossil fuels. As the push to harness natural sources of renewable energy sources grows, there is more willingness to invest in the development of ways to exploit those energy sources.

There are a variety of means by which tidal power can be harnessed. The oldest is the tidal barrage; historians believed that these were used even in medieval times before the development of electric power [3]. Tidal barrages are also the oldest modern means of generating electricity from tidal power. The oldest modern tidal water power plant used to generate electricity is the Rance Tidal Power Station in France, which was completed in 1966. It has a peak output of 240 MW and generates 540 GWh annually [5]. Several other similar plants dating from the 1960s and 1970s also exist around the world, but the new Sihwa Lake Tidal Power Station in South Korea with a capacity of 254 MW completed in 2011 has the largest capacity [6].

Essentially a modified dam, a tidal barrage captures rising tidal waters in a reservoir and then releases this water through turbines to generate electricity. The potential energy of the reservoir is a difference in the hydraulic head of the tides. During high tide, water flows in the barrage and is then released again during low tide. Control of the dam's sluice gates allows water in and out at appropriate times.

Another style of tidal water power generation is the tidal stream generator. Tidal stream generators are more like underwater wind turbines than the dam-like tidal barrage generators. Their functionality and placement are quite similar to the surface wind farms that have become common sights around the world. Tidal stream generators are not as common as tidal barrages however, and have yet to see widespread implementation or use for large-scale power generation.

Tidal stream generators make use of high-velocity tidal streams that are created by accelerating flow in narrow channels. These channels are natural features and thus tidal stream generators are limited to areas that possess the potential for a site. These sites are not uncommon however particularly around the British Isles and around the North Sea. The largest tidal stream generation sites are located in these areas, but even these sites have very small power capacity on the order of 10s of MW. Work moving forward will involve modeling to design optimum large-scale underwater turbine farms akin to surface wind farms [7]. Of course, like those same wind turbines, tidal water stream generators have a lot of potential to scale. A small set of turbines can be used in narrow channels, as has been done in New York City Harbor, and a large farm can be placed in wide ones.

The global prevalence of the channels needed for tidal stream generators gives them excellent potential for contributing a significant percentage of global power generation. Even small channels can generate megawatts of power and the largest channels can provide gigawatts [7]. If the design, installation, and maintenance of these generators can be standardized in the way that wind turbines have been, then they could make an even more significant and less variable contribution to global power demand. See Section 5.4 for further discussion of these difficulties.

A third method of tidal water power generation has been dubbed dynamic tidal power by its proponents. Though no power station currently uses dynamic tidal power, it has potential to eclipse both tidal barrages and tidal stream generators in terms of power generation and mitigation of environmental impact. Dynamic tidal power was first proposed by two Dutch engineers when they realized that tides also had significant motion parallel to the coast [8]. Traditional methods of extracting tidal power relied on tides washing in and out over the course of days. This meant that many potential sites for tidal power could only supply energy at certain times of day. Clever engineering solutions have managed to mitigate this problem somewhat, but not entirely. See Section 5.4 later for further discussion of this.

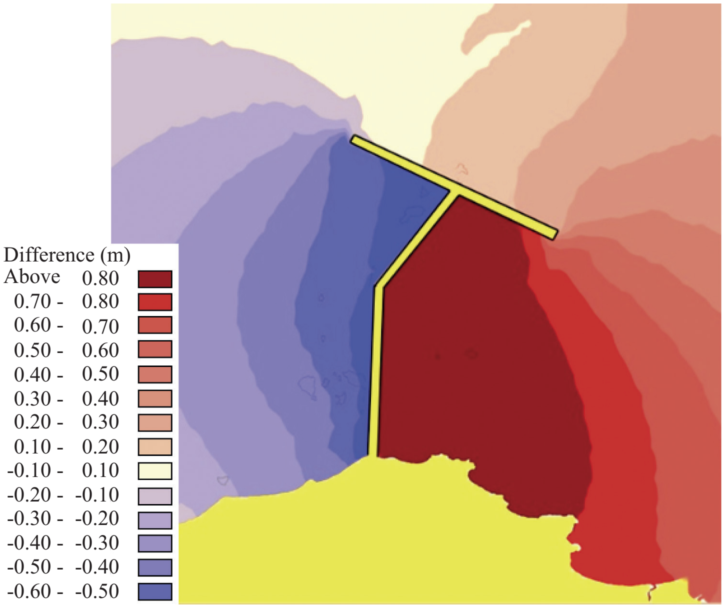

Figure 5.1. Head levels around a dynamic tidal power station [8].

Dynamic tidal power works by exploiting regions with naturally strong tidal currents parallel to the coast. A dam structure is built attached to the coast and extending out from it, as can be seen in Figure 5.1. Along the length of the dam, turbines are set into the structure in order to extract the hydraulic head that is created by the dam's presence. The end of this structure is capped with a T in order to enhance the head that the tidal waters will create naturally. Like tidal stream generators and tidal barrages, dynamic tidal power relies on specific natural characteristics of a region. Strong tidal currents parallel to the coast are necessary. Conditions like this exist in the North Sea, the Irish Sea, and the Yellow Sea [8]. Dynamic tidal power offers a good complement to the other two forms of tidal power extraction.

The advantage of dynamic tidal power is that it provides much more constant and reliable power supply; this is a major boon for any renewable energy source and something that neither wind nor solar energy can claim. Dynamic tidal power provides a more constant energy supply by using two power-generating structures set at the appropriate phase difference in the tidal system [8]. Dynamic tidal power also has the advantage, unlike tidal stream generators, of relying on the inertia of the tidal current, not its velocity. This means that the tidal waters do not need to be moving particularly quickly for them to be exploited [8]. It also allows for the use of relatively low-speed turbines, which is an advantage from an environmental perspective. See Section 5.4 for further discussion.

Each of these three methods exploits a different kind of natural tidal energy. Among the three, the number of potential sites for tidal power is very high. Rather than competing with each other, they can complement each other by providing a larger number of potential sites for tidal power extraction. The next section will discuss some of the particularly viable regions where tidal power could and often is being extracted.

5.3 PLACING TIDAL WATER POWER STATIONS

One important consideration with tidal water power generation is the placement of the power station. Much like wind, solar, and other water power stations, tidal power is dependent on location in order to be a viable energy alternative. Since large tidal forces are necessary in order to generate sufficient power, it goes without saying that coastlines, be they on lakes or oceans, with large tidal potential, are necessary to generate large amounts of power.

Power generation is very much an economy of scale and this need for large-scale power stations has been a limiting factor of many of the sources of renewable energy. Wind, water, and solar energy stations all tend to require large tracks of valuable land in order to generate enough power to be economically viable.

Tidal power is not an exception to this rule. In fact, the traditional tidal barrage stations consume valuable coastline territory and tidal stream generators can obstruct shipping lanes. Limiting these downsides, often by integrating the power stations with existing infrastructure, is a primary design consideration for most tidal power stations.

The need for high tidal potential areas also limits the use of tidal power stations to certain areas around the globe. Nevertheless, certain areas are prime with potential for tidal power stations. The Korean peninsula is one such area, and the South Koreans have made larger strides than any other country in harnessing the potential of tidal water power. The world's largest tidal water power station is the Lake Sihwa Tidal Power Plant in South Korea. This plant was completed in 2010 and surpassed the French Rance Tidal Power Station, the world's first and, up to that point, largest tidal power station [6]. The South Koreans have clearly been satisfied with the success of the Lake Sihwa Plant as they have already made plans for another tidal power plant at Incheon, South Korea's largest port, which will more than triple the capacity of the Lake Sihwa Plant.

South Korea is one of many East Asian countries that suffers from a lack of significant coal or gas reserves within its own borders. The rising costs of energy have put these small East Asian nations on the forefront of pioneering renewable energy technology. South Korea set itself a goal of producing 5 percent of its energy needs using renewable energy sources by 2011. The South Koreans' adeptness at taking foreign technology and improving it could be just the push tidal power requires to become an economically viable renewable energy alternative [9]. With South Korea's natural potential for tidal power in the Yellow Sea, the country has the potential to revolutionize this technology for the future.

The power station itself occupies only a small portion of the much larger Lake Sihwa dam that existed before the construction of the power station. This highlights a trend among tidal power stations. Both the Rance Power Station and the Lake Sihwa Power Station were built on existing infrastructure in order to minimize cost [5, 9]. The Incheon Power Station currently under construction in South Korea will also make use of existing infrastructure. This trend among tidal power stations is significant as it can lead to decreased capital costs in the construction.

The entire coastline of mainland China is also viable for implementation of tidal water power. The Chinese government is already making plans to include tidal water power in its 2020 goal of using renewable sources for 15 percent of its energy needs. China is keenly aware of its growing energy needs, which are already second only to the United States. It is also aware that its domestic resources are quickly being depleted by its surging consumption. It is for this reason that China has become a world leader in investing in renewable energy development despite its massive reliance on coal for power [10].

A major advantage for the Chinese in using tidal power over other kinds of renewable energy is this: Tidal power can be generated on the coast, very close to the major Chinese consumption centers. Other forms of renewable power, particularly wind and solar, would only be efficient in the remote northern and western regions of China [10]. Transferring the power across the length and breadth of mainland China would severely increase the cost of utilizing those energy resources.

Wang estimates in his report that China's 242 potential tidal water power sites could extract in excess of 110 GW. In particular, the East China Sea has the largest potential with the highest tidal head along the coast of mainland China. China also shares the Yellow Sea with South Korea, which provides another high potential area for energy extraction [10].

In fact, China has already made an attempt at extracting its tidal water power. In the 1970s and 1980s, in the wake of the success of the French Rance Tidal Power Station, China built many of its own tidal power stations. Unfortunately, due to poor site selection and planning, only three of these plants are still in operation and only one generates significant amounts of power. The Jiangxia Power Station is the only one of the three operational Chinese tidal power plants that operates at a profit. Want argues that with new knowledge and technology, China is past due for a second attempt at extracting its vast tidal resources [10]. The Chinese government appears to agree to some degree as it has begun working on new tidal power projects and has brought in foreign experts for recommendations on extracting tidal power.

Other Southeast Asian countries, wary of the growing cost of traditional energy sources and concerned with their own lack of such resources, have begun to consider taking advantage of their own renewable energy resources. As Khairul's report on potential sites for tidal water power stations explains, Malaysia is seeking to make use of tidal resources to meet some of its growing energy needs [11]. Malaysia, like other Southeast Asian countries, is a rapidly growing industrialized nation. This rapid growth translates to ever greater energy needs. The lack of the natural resources for traditional power generation, coal, oil, and so on, within their borders, means that these nations must turn to other sources of power in order to avoid paying ever higher energy costs.

Khairul used geographical information system (GIS) technology to identify the most promising sites along the Malaysian coastline for potential tidal water power stations [11]. His method of using available data to identify high-potential sites as well as estimate the potential energy output could be applied anywhere by someone with access to the appropriate GIS data to quickly evaluate the potential of an area for tidal power. This makes GIS a potentially powerful tool for combining meteorological, geographical, and infrastructure data to evaluate potential sites. In fact, this GIS technique is not limited to tidal power stations. It could be applied to identify sites for other types of renewable power as well including wind, solar, and wave energy stations.

The first large-scale on-grid commercial power-generating tidal stream turbines are the SeaGen turbines installed off the coast of Northern Ireland in the United Kingdom. These turbines generate approximately 1.2 MW for 18 to 20 hours a day when the tidal velocities are sufficient. As the first such installation, the impact of the SeaGen turbines has been closely monitored since their installation in 2008. These generators were installed as part of the United Kingdom's efforts to increase its use of renewable energy resources [12].

The British Isles have some of the greatest potential for tidal water power generation. Estimates by the British government show the potential for 15 to 20 percent of the United Kingdom's power needs to be met by tidal resources. In particular, the straits that surround the United Kingdom offer a lot of potential for tidal stream generators, which are very reliant on high-velocity tidal flows [12]. The SeaGen turbine has been in operation since 2008 successfully meeting its design goals, but financial troubles in the United Kingdom in the later months of 2008 have put plans for further expansion of tidal water power extraction on hold in the country. The United Kingdom still hosts Europe's primary marine energy research center, the European Marine Energy Center, in Orkney. There are still many proponents for tidal water power in the United Kingdom, but without government investment, large-scale implementation remains unlikely.

There are many potential sites around the world where tidal power stations could be installed to extract power very efficiently. A few of these sites are currently being utilized, but tidal power does not contribute a significant amount of global power at present. Further investment by governments with access to high-potential tidal power sites could help drive the technological innovation that will make tidal power even more practical. As the desire to make better use of renewable resources increases, there will be additional research and development of tidal power devices. This R&D will be necessary to overcome the engineering challenges associated with tidal power.

5.4 ENGINEERING CHALLENGES OF TIDAL POWER

There is an array of engineering challenges that are related to tidal water power. Overcoming these challenges will be essential to the large-scale implementation of tidal water power in the world. Many of these challenges are at the heart of what is forestalling the wide use of tidal water power at this moment.

One major challenge for tidal water power when compared to the more traditional hydroelectric dam is the periodic nature of the water flow. For a hydroelectric dam, power generation is dictated more or less only by the level to which the sluice gates are opened. Supply can be tailored to meet demand, subject to only the limitations of the level of water in the reservoir, not so with tidal power. The tides are naturally a periodic motion and developing technology to harness that periodic motion is more difficult than for the traditional hydroelectric dams.

For tidal barrages, this challenge presents itself through the reality that tides wash in over the course of hours. Careful management of reservoir levels is necessary to maintain constant power output. This also dictates peak times of power generation based on the natural motion of the tides, and not necessarily peak periods of demand. Tidal barrage turbines however do not have to deal with the periodic wave motion and can function exactly like those on traditional hydroelectric dams. This is a major advantage of tidal barrage systems and a primary reason why implementation of these systems is more common than other types of tidal power generation [13].

The primary difference between tidal barrage turbines and those in traditional hydroelectric plants is the extremely low hydraulic head driving the turbine. Using conventional turbines, the cost of generating power is inversely proportional to the head, and the low head of tidal power stations makes tidal barrages less cost-effective than hydroelectric dams [13]. Takenouchi's suggestion of using reciprocating turbines designed for low-head situations offers one solution to increasing the cost-effectiveness of traditional tidal barrage power stations. As he notes, however, the optimal turbine is determined by site characteristics and by the size of the power station [13]. His suggestion of using wave power devices for very small stations presents a potentially valuable means of power generation for very small, remote, coastal sites. Wave energy devices have the advantage of favorable maintenance cost to capital cost that makes them desirable in such applications.

For tidal stream generators and particularly for proposed dynamic tidal power models however, turbines must be designed to be bidirectional as the wave motion driving the turbines will be inherently periodic. Handling the periodic nature of this wave motion is both a mechanical challenge and a control challenge. Bidirectional turbines exist, but they suffer from efficiency losses when compared to single direction turbines. Vennell and others consider the need for bidirectional turbines in tidal power devices a sort of cost of doing business. Bidirectional turbines feature symmetric airfoils operating at high angles of attack. Fortunately, the much higher density of water reduces the problems of stall and flow separation with the blades [7]. Solving some of the efficiency problems of tidal turbines without expensive mechanical systems could lead to large improvements in the energy-generating capability of tidal power.

The irregular reciprocating motion of waves that generate tidal power makes power extraction more difficult than wind, solar, or other forms of water power extraction. A consequence of this is the lack of standardization in tidal power generation devices. Where wind power devices have adopted a single common form, tidal power devices have yet to settle on a single design. This can be seen in the three general concepts presented in this chapter as well as in the variety of devices designed for harnessing wave motion energy that have been presented over the years. Examples of some of these devices can be seen in Ringwood's discussion of wave energy conversion [14].

It is important to note here that wave energy and tidal energy are not interchangeable terms. Wave energy is the energy imparted to surface waves by the wind and it thus derives its energy from the sun. As stated in Section 5.1, tidal energy stems from the gravity and motion of celestial bodies. The two concepts are closely related however and share many engineering challenges related to their application. For example, areas with high potential for tidal energy generation frequently have high potential for wave energy generation and vice versa [14].

The study and modeling of waves that are necessary for efficient extraction of wave energy are closely related and often applicable to the modeling required for efficient extraction of tidal energy. Ringwood's treatise on developing control methodologies both for individual wave energy devices and for the large-scale wave energy farms makes use of modeling data that could also be applied to tidal energy extraction. He argues that efficient extraction control techniques that are less sensitive to error and the inherent variability of waves are major obstacles in the path of large-scale implementation of the technology [14]. The same might be said for tidal power generation.

Vennell's primary discussion does not deal with the efficiency of individual tidal stream turbines, but rather with the arrays of turbines that inevitably become necessary to extract large amounts of power from the tides. Even the smallest channels used from tidal stream power make use of multiple turbines. No one turbine can successfully harvest all the power present in a stream. Vennell stresses the point that there is no simple relationship between the installed capacity of the turbines in an array and the power capacity that an array is capable of generating [7]. As such, designing large arrays of tidal stream turbines has become an area of interest for many who are proponents of tidal water power.

Vennell makes a very compelling and interesting case for how to go about installing large arrays of tidal stream turbines. He notes a few important considerations as well. In order to efficiently extract power from a channel, the turbines need to occupy less than 5 percent of the channel's width. Arrays must also be designed with considerations made for traffic through the channel and for maintaining an environmentally friendly flow [7]. More discussion on the need for environmentally safe tidal water power is found later in this section.

To date, all the large-scale commercial tidal stream generators use only a few turbines arranged in a line. There are no "farms" of tidal stream turbines as have become common with wind power turbines. This is partly due to the difference between extracting power from water and from air. Tidal stream generators cause considerably more disturbance to the medium than do wind generators. As such it can be difficult to arrange tidal stream generators in a way that maximizes power output. In fact, one of the main concerns with large farms of tidal stream turbines is that they will interfere with each other to such a degree that it will negatively affect the lifetime of the downstream turbines [12]. Thus, attention must be paid not only to maximizing the output of the array, but also to avoid damage to the turbines.

All of the problems discussed so far are related to the ability of tidal water power to efficiently extract energy. These problems have been related to making tidal water power an economical alternative to traditional power sources. It is important, however, to keep the long-term goal of renewable power sources in mind, that is, to save the planet from the destruction caused by traditional fossil fuels. As such, it is important that the new renewable power sources considered are not themselves harmful to the environment. While intuition might tell us that it is obvious that tidal water power will not cause harm, engineers prefer to be sure of these things. As such it is not surprising that almost all reports treating on tidal water power discuss, in some way, the environmental impact of tidal water power.

From the French [5], to the South Koreans [6, 9], to the Chinese [10], to the British [12], all discussions of tidal water power include studies on what effect tidal water power generation will have on the environment. The SeaGen tidal stream generators were considered a feasibility study by the UK government. Part of what was studied was whether the turbines would prove dangerous to the local aquatic wildlife. Studies have found that most of the local wildlife avoids the area around the turbines, and there have been no reports of wildlife being killed by the blades. Some were also concerned about the sound the blades created affecting animals that communicate via echolocation, but studies have found that the acoustic impact of the turbines is lower than the regular shipping traffic that travels through the area [12]. As the largest tidal stream generators in the world, the SeaGen turbines serve as the best current benchmark for the low environmental impact of tidal stream power.

The case for tidal barrages is a little harder to make than for tidal stream generators. Tidal barrages operate much like hydroelectric dams in many senses and their environmental impact is one of those. The reservoirs created by the construction of tidal barrages inevitably affect the local wildlife. Techniques for protecting wildlife from the turbines that have been developed for hydroelectric dams are employed with success by tidal barrages, but the creation of a large reservoir on the ecosystem of an estuary or bay is not so easily mitigated.

Parker deals extensively with the potential impact of tidal barrages on the environment. He discusses in particular the effects of creating a large reservoir on local flora and fauna, the potential compounding of the effects of local sources of pollution that find their way to the reservoir, and the conflict with use of the reservoir as a site for leisure activities and environmental concerns. As he says however, each of these concerns is site specific and not something that can be easily generalized [15]. It is simply important that those proposing the construction of tidal barrages for power generation make the appropriate considerations for the effects of such a project on the environment.

Dynamic tidal power is not immune to environmental concerns either. Care must be taken that the construction of the dams does not negatively impact the local ecosystem. Fortunately, this is an area where dynamic tidal power has an advantage. Because the dam does not create an enclosed area, many of the concerns that can be major roadblocks for a tidal barrage do not apply for dynamic tidal power. Additionally, dynamic tidal power makes use of low-speed turbines much like those of tidal stream generators and thus have a similarly low impact of local fauna, both in terms of direct contact with the animals and acoustic impact [8].

It is not always a rule that the presence of human infrastructure must be harmful to the environment. A prime example is the large cooling canals of the Turkey Point nuclear power station in southern Florida, which have become a wildlife sanctuary since the construction of the plant. Thus, with careful planning and foresight, it is possible to integrate tidal water power into an ecosystem without large negative environmental effects.

Despite all these challenges, tidal water power has incredible potential for large-scale usage. It also has many advantages over other forms of renewable power and especially over traditional nonrenewable sources. Tidal water power's close relation to hydroelectric dams in terms of applicable technology means that much of the technology for tidal water power is already very mature and widely utilized. Those seeking to implement tidal water power should strongly consider using mature technologies wherever possible to mitigate costs.

5.5 CONCLUSION

There is a considerable amount of natural renewable energy in our planet. Most of it currently is unexploited. As the need for new sources of energy has grown, humans have been attempting to harness this energy. Though in some ways we have known how to make use of these resources since before we used electricity, in other ways, we are constantly discovering new, better ways to extract energy from our environment without doing irreparable harm to it in the process. Conscious of the harm we are doing, we have attempted to shift away from using nonrenewable energy sources to less-polluting and more reliable forms of energy. Whether using nuclear power in the short term or attempting to harness the sun as the single greatest source of power on our planet, humanity has made great strides in power generation in recent years.

This chapter has attempted to make a compelling argument for the case of using tidal water power as a major contributor to the rising global energy need. In particular, the advantages of tidal water power as a more reliable and consistent form of energy than solar or wind power were discussed. Several potential locations were discussed where tidal power could be used to generate considerable amounts of power. Many of the countries with natural tidal resources have already begun attempts to exploit those resources to reduce their use of nonrenewable energy sources.

Additionally, some of the current limitations of tidal water power technology were discussed and areas of potential future research and development were suggested. Both on the scale of individual devices where improving efficiency is a constant engineering goal and on the larger scale of whole arrays and facilities where developing systems that can make efficient use of resources to deliver consistent power, there is room for improvement of tidal water power.

Finally, the environmental impact of installing tidal water power stations was discussed relative to the value of installing such stations on mitigating further damage to the planet by fossil fuel consumption. It was argued that care must be taken to ensure that as little environmental damage is done as possible. Tidal water power has the potential to be a major source of energy for human civilization and its unique source from gravity rather than solar power makes it an important diversification of our renewable energy sources.

However, as a final point, it should be noted that no single source of energy will single-handedly solve the world’s energy needs. The goal is to replace the rapidly diminishing and highly polluting fossil fuel sources with many different kinds of renewable sources. Tidal water power is only one of many such renewable sources and it is necessary for the development of human civilization that a diverse range of renewable resources be cultivated as our energy needs are sure only to grow in the future.

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CHAPTER 6

Natural Gas Resources in the World

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6.1 INTRODUCTION

As both the political and environmental ramifications of continued use of coal and oil as primary sources of energy become graver each day, it is no surprise that a large focus of modern engineering is on the determination and efficient utilization of alternative fuel sources. Of these alternative fuels, natural gas has increasingly garnered attention over the last few years. Though its use as a source of energy dates back to the early 19th century, it is only in recent endeavors that it is sought to change its application from simple household heating and appliances to large-scale power production and automotive fueling. Though support has been rallied on several fronts for its widespread use due to cleaner combustion relative to oil and coal and its strategic source locations, the use of natural gas is not free of controversy, where concerns mainly lie in the effects of certain extraction techniques (i.e., fracking) and politics.

This chapter will analyze the feasibility and implications of using natural gas as a leading fuel source, primarily as a study of its availability in terms of location and quantity, and the corresponding political and social implications of tapping into these resources.

6.2 NATURAL GAS

The Environmental Protection Agency describes natural gas as a fossil fuel created when plants and animals are buried under high pressure and subjected to intense heat over several millennia [1]. As natural gas is formed (essentially gaseous petroleum), it has the ability to rise upward through porous layers of rock until reaching an impermeable layer (the reservoir) from which it is extracted through drilling [2, 3]. Natural gas is a mixture of several gases, with the greatest contributor being methane (typically 84.07 percent in terms of mole fraction). Methane serves as the primary hydrocarbon that allows energy release through combustion. Inorganic gases such as carbon dioxide and nitrogen are typically present in small amounts and reduce the efficiency of the fuel since these gases are incombustible [3].

The available energy in a given volume of natural gas largely depends on the amount of inorganic gases present in the mixture. Guo claims that anywhere from 700 to 1,600 Btu of energy can be released during the combustion of 1 cubic foot of natural gas, where the higher end of released energy corresponds to lower amounts of inorganic gases present [3]. As compared to other fuels, similar to hydrogen, natural gas has a higher specific energy per unit mass than other fossil fuels (such as gasoline), but has a lower energy capacity per unit volume [4].

Thus, though requiring more volume to produce the same amount of energy as some other fossil fuels, natural gas has still shown itself to be predominant. This was made evident by the fuel becoming the second most consumed source of energy, displacing coal, and only falling behind oil by the year 2000 [3]. This is due to several benefits of using the fuel including, as stated by Karim, cleaner burning than coal or oil, high combustion efficiency, lack of need of expensive fuel-storing facilities, and simpler and cheaper burner equipment, among many others [4]. However, natural gas is a nonrenewable resource (as previously stated, it takes several millennia under the right conditions to produce the fuel). Thus, with the increasing widespread use of natural gas, several concerns arise in relation to how much of this resource is available, where is the resource available, how long will this resource be available, and the corresponding political and social implications.

6.3 AVAILABLE RESOURCES

Equipped with the knowledge of the benefits of natural gas, the next logical step in its study is to analyze its feasibility of use more prominently as a major world energy source. Thus, critical to the question of its utility is how much of it is available? Where are these resources? How much gas is located in these resources? How feasible is extraction at these locations?

The International Energy Agency (IEA), an international organization composed of 29 countries (including the United States) with the goal of ensuring a future of clean energy, claims that global proven natural gas reserves are estimated to be as large as 190 trillion m^3. Proven gas reserves are defined as reserves that can be harvested using current technology and can be done so in a way that is economically feasible to maintain current gas prices. Conventional natural gas reserves that are believed to be recoverable in the future, either through discovery or progression of technology, are estimated to be much larger, at a more than double 400 trillion m^3 [5]. BP's latest yearly *Statistical Review of World Energy* yielded a concurring estimate of proven natural gas reserves of 185.7 trillion m^3 (at the end of 2013) [6]. Natural gas reserves can further be broken down into conventional and unconventional reserves, where unconventional reserves represent those that are more difficult to extract (such as shale gas, tight gas, and coal-bed methane). It is believed that unconventional gas makes up 45 percent of the entire world's resources of gas that is recoverable. Unconventional gas plays an interesting role in the global gas market though it is more difficult and expensive to extract (and may require controversial extraction techniques such as fracking) than conventional gas, and it is geographically more equitably distributed. Therefore, with increasing demand of natural gas, the IEA is expecting unconventional gas resources to be tapped from the 14 percent used today, up to around 32 percent by the year 2035 [7].

Though knowing the total amount of natural gas available in the world is useful as a preliminary overview of the quantity of the resource available, location of these resources is of paramount importance to future more widespread use of natural gas. Energy being one of the most politically charged topics means that there are many implications as to the country and type of gas reserve where the resources are located. Relations among nations with regard to importing and exporting, embargos, tariffs, and ambitions to dominate the market will affect how these resources are tapped, as well as environmental concerns relating to how the gas is acquired. It is estimated that as much as 80 percent of the entire world's proven gas reserves are located in only 10 countries [8]. Politically, this gives some countries, which may have the ability to supply their own needs for gas as well as export to others, a degree of influence over other countries that have to rely on imports.

6.3.1 EURASIA

If one looks by continent as to where natural gas is located, one would find one of the largest amounts being located in Europe. In actuality, these results are skewed. Russia (considered as both part of Europe and Asia) dominates as the country with the world's greatest amount of natural gas reserves, whereas western European countries (and most eastern) contain very little. Even further, possessing approximately 1,688 trillion $ft.^3$ (~48 trillion m^3) proven reserves, the Russian Federation contains around a quarter of all the present proven reserves on earth (as of January 2013). Of Russia's resources, it is claimed that half are located in Siberia (Asia), with the majority of that amount contained in the Urengoy, Yamburg, and Medvezh'ye gas fields [8].

The Urengoy gas field is claimed to be the second largest in the world. Located in the northern West Siberia Basin, the field is said to contain upwards of 10 trillion m^3 of gas deposits (total). Yamburg, the third largest natural gas field located also in Siberia, is claimed to contain 8.2 trillion m^3 of natural gas, and having production exceeding 200 billion cubic meters a year. The Medvezh'ye gas field in Siberia has also played a large role as 80 percent of its reserves have already been extracted (though it still contains 1.5 trillion m^3 of gas). These three Siberian reserves comprise approximately 45 percent of Russia's reserves. Other Russian gas fields of importance are the Orenburg (largest outside of West Siberia), Schtokman, Zapolyarnoe, Kharasavey, and Bovanko [9].

Government officials in Russia frequently capitalize on the political influence these resources grant them. The Russian Minister of Natural Resources and Environment revealed that it is key for the interests of the Russian Federation to make known that they are in possession of more natural gas reserves than any other country to promote investment [10]. More importantly, Russia obtains significant political leverage through its export of fossil fuels (including natural gas) to the European Union (EU). The EU, having little reserves itself (especially), is considered the world's greatest importer of fossil fuels. Twelve gas pipelines extend from Russia to Europe, and it is estimated that the EU imports 50 percent of its natural gas, of which 40 percent comes from Russia [11]. As conflicts among the United States, EU, and Russia persist, the energy dependency of Europe on Russia gives Russia the ability to flex its muscles. As the United States and EU impose sanctions on Russia, Russia in turn threatens to shut the pipelines of natural gas to Europe. The consequences would be severe as it is stated that 12 out of the 28 members of the EU rely on Russia for more than 50 percent of their natural gas while six more rely on Russia almost completely for gas resources [12]. Some even postulate that current conflicts in Ukraine are partly the result of these energy issues as Ukraine recently has chosen Western energy companies to aid in extracting Ukrainian gas resources, even though two major Russian pipelines already transport gas through the country [11]. However, Russia's influence as a result of natural gas demands is not limited to Europe. The mostly Russian state-owned gas giant Gazprom made a deal back in 2009 exporting half a billion cubic meters of natural gas a year for five years to the United States [13].

Outside of Russia, the second largest reserve in Eurasia (excluding the Middle East) is in the nation of Turkmenistan. This central Asian country holds the fourth largest natural gas reserves in the world, with proven reserves between 10 and 20 trillion m^3. Reserve locations include the Dauletabad field, the Amu Darya and Murgab South Caspian basins, and the South Yolotan area. Exportation is considered difficult due to pipeline limitations though Russia does import from Turkmenistan. It is also stated that China is the only foreign nation involved in natural gas extraction in Turkmenistan [6, 8].

6.3.2 MIDDLE EAST

Though Russia dominates as the nation with the largest gas reserves in the world, the Middle East remains the global region with the most natural gas. However, the production of natural gas by volume is less by all Middle Eastern countries combined than by Russia itself [6]. Iran sits as the country with the second largest natural gas resources in the world. Proven natural gas reserves are estimated at 1,187 trillion $ft.^3$ (33.6 trillion m^3). Of these reserves, it is noted that 60 percent are located offshore with the South Pars being the largest natural gas field. Other major fields in Iran include North Pars, Kish, and Kagan [8]. The Pars Oil and Gas Company describes the South Pars field as a reservoir in the Persian Gulf between Iran and Qatar. Approximately 3,700 of the 9,700 km^2 of the reserve belonging to Iran contain 14 trillion m^3 of natural gas (close to half of Iran's reserves) [14].

Though Iran is the second largest holder of natural gas reserves in the world, most of its resources are not developed. International sanctions on the nation's government have impeded growth of this market for the Middle Eastern nation. Thus, Iran is faced with an absence of foreign investments and other means of financing that would allow it to become more prominent in the natural gas industry, though some export and import occur among Iran, Turkmenistan, and Turkey [15]. Despite these sanctions, growth of natural gas production is expected in the next couple of years. Iran recently announced its opening of the largest liquefied natural gas (LNG) storage facility, Shourijeh, in the Middle East, which will be capable of supplying 4.8 billion m^3 of natural gas. It is stated that it is the goal of Iran to increase its natural gas production by 200 million m^3 within the next two years with the hope of eliminating imports from Turkmenistan [16].

Though Iran contains the largest natural gas reservoirs in the Middle East, there are several other countries in this region that make up the top 10 countries in terms of volume of proved reserves. Of these, Qatar is second in the Middle East and third in the world. Proven natural gas reserves in this nation total 900 trillion $ft.^3$ (approximately 25.5 trillion m^3), which is close to 14 percent of the total proved reserved of earth [17]. Advantageous to the nation, Qatar holds the largest nonassociated (reservoirs that are solely natural gas/no oil) reservoir in the world: the North Field. This offshore reservoir located in the Persian Gulf is almost the size of Qatar itself and makes up the majority of a field in which Iran's South Pars field makes up the other share [8].

Much of Qatar's motivations and actions concerning its natural gas productions have been politically oriented. Before the 1980s, it was stated that Qatar was primarily concerned with oil production. This proved lucrative during the 1970s and led to a great increase in social welfare programs in the nation. However, oil prices dropped in the 1980s causing financial stress on Qatar. Simultaneously, Iran and Iraq were at war, attacking oil tankers in transit in the Persian Gulf. Qatar, knowing that it could never prove to be comparable to Saudi Arabia in terms of oil production made a strategic move to improve its foreign policy. Thus, Qatar changed its focus to become the "Saudi Arabia of natural-gas production," a fuel it contained in vast amounts but mostly ignored. This move bolstered its independence in foreign policy and garnered Western support in terms of protection from Iran and Iraq [18].

Today, Qatar is the world's leading supplier of LNG [8]. LNG provides the distinct advantage of making natural gas intercontinental transportation economical. By liquefying natural gas (by a process that cools the fuel to −260°F [−162°C] and compresses the fuel to one six-hundredths of its volume), the natural gas can then be transported via LNG ships, and then warmed back to a gaseous state upon reaching its destination [19].

Also prominent in the Middle East in terms of quantity of natural gas resources is Saudi Arabia. The oil giant stands as the sixth in the world in terms of natural gas reserves with just over 8 trillion m^3 in proven reserves. Though Saudi Arabia is in the top 10 nations with greatest natural gas reserves, the country neither imports nor exports the fuel. All gas produced by the country is consumed by the country [8]. In total, Saudi Arabia still produces approximately 3.6 trillion $ft.^3$ (around 102 billion m^3) of natural gas a year where well over half of this amount is from only three fields. These are Ghawar (over 60 percent of total production), Safaniya, and Zuluf, all associated gas (gas in the presence of petroleum) reserves. Natural gas production is restricted by the high cost of exploration and extraction, though it is still expected to increase. The national oil and gas company of Saudi Arabia, Saudi Aramco, has begun negotiations with Kuwait to develop the offshore Dorra field (in a Saudi–Kuwait neutral zone). Furthermore, Saudi Arabia has begun preliminary allowance of private investment for further reservoir exploration [20].

To conclude the discussion on natural gas resources in the Middle East, natural gas resources located in the United Arab Emirates (UAE) will be considered. The UAE is said to have natural gas reserves of up to 215 trillion $ft.^3$ (6.1 trillion m^3) making its seventh in the world in terms of volume. It is stated that close to 94 percent of the UAE's natural gas is located in Abu Dhabi, while the rest is located in Sharjah and Dubai. Despite its vast reserves, the UAE imports the majority of its natural gas resources (mostly from Qatar, at approximately 616 billion $ft.^3$/17.4 billion m^3 in the year 2011 alone) [8].

The reasons for the UAE's net importation of natural gas are threefold. First, the UAE reinjects a large portion (over a quarter of its production from 2003 to 2012) back into its oil fields. This is part of an enhanced oil recovery technique called gas injection to increase oil flow rate. Second, the country's electric power plants (described as inefficient) are mainly fueled by natural gas. Third, there are complications concerning the quality of the UAE's natural gas. The gas it possesses in their own reservoirs is said to contain high amounts of sulfur (which is undesirable as it causes corrosion among other difficulties). Purifying the gas is both difficult and expensive and has only proved to be economically feasible as of late due to technological increases [21].

6.3.3 AFRICA

Though a large volume of the natural gas in the world exists in Russia and the Middle East, there are other notable gas reserves existing in other continents. Specifically, Africa is claimed to have vast untapped resources and could become a major player in the natural gas market if the initial financial and technical hurdles can be overcome. As a whole, it is estimated that Africa contains 7.5 percent of the world's natural gas reserves, totaling 494 trillion $ft.^3$ (around 14 billion m^3) of proved reserves. Advances in natural gas production could provide great economic, and thus subsequently social, gains for these gas-wielding nations [22].

Of these countries, the most prominent is Nigeria, the nation with the ninth largest natural gas reserves in the world. Nigeria is stated to contain 182 trillion $ft.^3$ (5.2 billion m^3) of proven reserves. The resources are located mostly in the Niger Delta, extending into the Gulf of Guinea, with the most critical fields being the Amenam-Kpono, Bonga, and Akpo [8]. Though Nigeria is the richest country in Africa in terms of natural gas resources, the nation has fought against political corruption, which has inhibited proper policy regarding the energy state of the nation as well as violence related to ethnicity and religion that has impeded foreign investment [22]. Despite this general trend, Shell has had a presence in Nigeria in the production of natural gas.

Also prominent in terms of gas reserves is North Africa. Three out of the four countries (Algeria, Egypt, and Libya) with the greatest reservoirs in Africa are located in this region. Together, Nigeria, Algeria, and Libya account for 88 percent of all the gas produced in Africa. Specifically, Egypt is considered the largest consumer of natural gas in all of Africa (initially its produced gas was for domestic use, but as of recently it has begun engaging in exports and thus facing a slight domestic shortage). Additionally, Algeria is ranked 10th in the world in terms of volume of gas reservoirs. The country is estimated to contain 159.1 trillion $ft.^3$ (4.5 trillion m^3) of proven natural gas. Important gas fields in this country are the Hassi R'Mel (over 50 percent of its proven reserves are located here), Rhourde Nouss, Alrar, and Hamra [8]. The nation is said to be desiring further exports, even though it is considered Europe's second largest supplier. Outside of North Africa, the nation of Angola has shown increases in proven gas reserves and is a promising location for future exploration [22].

Social unrest and political conflicts in Northern Africa, primarily in Libya, have generated concern over the ramification spilling over to the European market to which they supply. Thirty-five percent of Italy's natural gas, 20 percent of Spain's, as well as other parts of southern Europe are provided by these two countries. Furthermore, Algeria is said to export around 20 billion m^3 (just 2010 alone) of LNG to Europe. The civil unrest and sanctions previously imposed on Libya have already caused disruptions in the past in Europe. However, major concerns are with the conflict spreading to Algeria, a much larger exporter to Europe than Libya. Thus, several proposals have been written concerning what Europe's response should be if a gas shortage were to ensue due to potential supply cuts caused by Algerian civil unrest [23].

6.3.4 THE AMERICAS

Though Eurasia, the Middle East, and Africa are proven critical figures in the current and future development of natural gas, one of the most important players today in the natural gas market is the United States. Overall, the United States is ranked fifth in the world in terms of volume of proven reserves, totaling around 334 trillion $ft.^3$ (9.5 trillion m^3). However, this number is still increasing due to continued exploration and the furthering of technology. Though globally fifth in volume, the United States is the world's leading producer and consumer of natural gas. In the year 2012 alone, the nation produced approximately 24 trillion $ft.^2$ (~680 billion m^3) of natural gas and consumed 25.5 trillion $ft.^3$ (~720 billion m^3). The most prominent locations of shale gas are the Barnett play (the largest in the United States) in Texas, Haynesville play between Texas and Louisiana, the Marcellus play in the Appalachian Basin, the Fayetteville play in Arkansas, the Woodford play in Oklahoma, Texas, and the Eagle Ford play in South Texas. The United States has over 305,000 miles of gas pipelines stretching across the country [8].

The largest, and arguably most important, development in the United States regarding natural gas is in regard to shale gas. Shale gas is natural gas trapped in the sedimentary rock known as shale. As of only 10 years ago, attempting to extract shale gas was economically unfeasible; however, great advances in technology in the United States within this short period of time have been made, and today, extraction of natural gas from shale is the leading source of production in the United States. These developments have changed the United States from the outlook of having to rely on imported LNG to meet future demands to the possibility of eliminating natural gas imports and becoming a net exporter, and eventually a leading LNG exporter [24].

However, exploitation of U.S. shale gas has not been without controversy. The common extraction technique known as hydraulic fracturing "fracking" has garnered as much opposition as support since its inception. Though this method has allowed the United States to transition to potentially becoming a leading exporter and caused gas prices to drop in the country, many are concerned about its environmental effects. In essence, the process uses high-pressure water, sand, air, and chemicals to fracture the shale around the drilling area to release the gas from the surrounding rock. Concerns have arisen that through the fracturing process, certain carcinogens may enter neighboring groundwater since a portion of the fracking fluid is unrecoverable [25]. Investigation has been made by the U.S. House Energy and Commerce Committee to better determine and address the consequences of fracking as a means of extracting natural gas [26].

North America is not the only continent in the western hemisphere with large proven gas reserves. In South America, Venezuela is listed as eighth in the world in terms of volume of proven natural gas (approximately 195 trillion $ft.^3$, i.e., 5.5 trillion m^3). Since Venezuela is a major oil-producing country, it is expected and, as is the case, it contains almost entirely associated gas as its reserves. Major gas fields include Anaco, Yucal Place, and Barrancas (located on the mainland) and Marsical Sucre, Blanquilla-Tortuga, Plataforma Deltana, and those in the Gulf of Venezuela (all offshore) [8]. Additionally, though not in the top 10 nations with proven reserves, Argentina can be of prime importance in the future gas market. The country is home to the second-largest shale-gas reserve in the world (as much as 308 trillion $ft.^3$ or 8.7 trillion m^3). The majority of this is located in the Vaca Muerta shale formation (a region that is said to be close in size to the country of Belgium). If the gas can be extracted from this region, Argentina could provide gas to the nation for 150 years while still exporting the fuel [27].

6.4 DISCUSSION AND CONCLUSION

Natural gas has elicited a great deal of controversy regarding its future role and potential impact in the energy market. From the considerations of this study alone, it is easy to see why some may view the fuel as the answer to the problems posed by coal and oil. That is, emissions harmful to the environment are cut significantly (around half the carbon dioxide emissions of coal, one-third of the nitrogen oxides, and almost no sulfur oxides or mercury compounds [1]). However, many argue that natural gas is not a long-term solution as its combustion still releases unwanted emissions, even if they are less than other fossil fuels, and because it is a nonrenewable source of energy. Furthermore, others point out that even though environmentally it is more favorable than coal and oil, consequences of unconventional gas extraction techniques (i.e., fracking) may be causing different types, but just as much concerning, of environmental and health problems.

It was also shown how foreign policy is greatly affected by natural gas. A future of increased natural gas usage would change the political landscape surrounding energy significantly. Already, the subject has caused waves on a global scale. Specifically in the United States, domestic policy concerning the environment and energy as well as foreign policy will need to evolve as natural gas evolves into a more prominent position in the energy market. Though fracking has caused a boom in the United States as it relates to natural gas, public concerns about the environmental and potential health risks will need to be addressed. As was stated, the United States believes itself to be in a position, because of this technology, to become a leading exporter of the fuel. Thus, if the U.S. government decides to impose restrictions on fracking, there would be resulting setbacks in the progress of achieving this goal. In the eastern hemisphere, Russia has already begun using gas as a way to flex its muscles against imposed sanctions from the United States and EU, and similar sanctions have inhibited Iran (the country with the second largest natural gas reserves in the world) from much production. Similarly, civil unrest in northern Africa has been a cause of concern since parts of southern Europe depend on gas lines stemming from Algeria and Libya.

Thus, it remains in question if natural gas will prove to be the next great source of energy. It seems that as far as current prospects are concerned, it is a possibility, if only temporarily. Natural gas is as a fact a nonrenewable energy source and as far as the United States is concerned, the Energy Information Administration only predicts that its "technically recoverable" reserves (proven and unproven reserves), at the gas consumption rate in 2011, will last only around 92 years [28]. To summarize, natural gas is abundant globally, yet limited in use over time; cleaner during combustion than other hydrocarbons, yet produces emissions; and produces more energy per mass than coal and oil, yet requires a larger volume and is thus difficult to transport. Overall, natural gas seems to be a better alternative than continued combustion of coal and oil for domestic and industrial power and will, due to the diversity of nations holding its resources, provide interesting political implications in the years to come. However, natural gas does not represent the achievement of the goal of clean sustainable energy. Instead, it can be considered a stepping stone in the right direction.

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CHAPTER 7

Deep Sea Oil Drilling and Its Future

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7.1 INTRODUCTION

The world is consuming oil at an alarmingly increasing rate. In 2013, the world consumed 90.3 million barrels of oil per day on average. That being compared to the 90.1 million barrels per day produced [1], the consumption of oil is only increasing. Therefore, there are massive efforts being made to find, access, and retrieve more and more oil. One of these methods is offshore oil drilling, specifically deep sea oil drilling. Offshore oil drilling started in 1947 and consisted of a drilling deck no larger than a tennis court and a few refurbished naval barges. The ocean floor was only 15 ft. below the surface located about 10.5 miles off the coast of Louisiana [2]. Today, technology has allowed us to reach oil that originally was thought to be far out of reach and the bar is continuing to be raised. There are many types of platforms for an oil rig drilling setup. Currently, the two main setups are semisubmersible platforms, also known as semis, and then there are ship-based oil platforms for drilling. Perdido is currently one of the most advanced semis to date, currently being used by Shell. It is a category of semisubmersibles called a SPAR. A SPAR is an oil platform comprised of a massive cylinder that floats upright in the ocean. The bottom of the cylinder is counterweighted to have its center of gravity well below its buoyance center ensuring that the platform stays upright even through hurricanes as powerful as Katrina. Perdido was the world's deepest direct vertical access SPAR. It houses a crew of 150 workers and can produce 130,000 barrels of oil equivalent per day. That means it can fill roughly 132,000 cars with gas every single day. All this is being done at a depth of 8,000 ft. below the water's surface [3]. The Perdido uses its large cylindrical body to store and assemble the drilling pipes making the vessel stronger. This allows for heavier, and stronger, drill pipes and casings to be used making the 8,000-ft. depth possible. The process of drilling for oil is relatively the same for most platforms. Once a site is found to have potential oil deposits using seismic and sound waves, an initial hole is drilled for the casing, which is a metal tube roughly 36 in. in diameter.

The casing extends 300 to 400 ft. into the seafloor. Next a drill bit is lowered from the platform by connecting drill tubes and extending it down to the seafloor. The drill bit is lowered inside the casing and the drill starts to rotate via the drill tube connected to the surface. It drills into the ground and simultaneously injects fluid, or mud, into the hole to push the debris to the surface where it is then separated and the mud is recycled. This process goes on until the bit reaches a predetermined depth and then it is retracted back to the surface. The next step is to lower a 22-in. diameter casing into the drilled hole. The casing is secured in place by injecting cement into the area between the outside of the casing and the wall of the hole. Now, before any more drilling occurs, a blowout preventer (BOP) is attached to the top of the 36-in. casing at the top of the well. Its purpose is to prevent the high-pressure water and oil from escaping the well when drilling. If a blowout occurs without a BOP, then the oil can escape the well and flow into the ocean or it can even come up in the mud and oil and gas can fill the platform at the surface causing an explosion. After the BOP is installed, the cement is dried and the process of drilling and cementing can be repeated with smaller and smaller diameter casings and drill bits until the oil is reached. And then the oil can be retrieved. The complications with ultra-deep-sea drilling comes from the massive pressures at greater depth as well as high temperatures experienced when drilling so deep into the earth's crust. This is what limits the oil exploration and stronger and lighter casings, drill pipes, and safer BOPs are things that need to be upgraded for deeper oil exploration.

7.2 BP'S PROJECT 2K

Currently, the industry standards for marine oil drilling is that the system can withstand a pressure of 15,000 psi at the seafloor. That has gotten the industry to the 8,000 to 9,000 ft. mark. But now there is a need for deeper, and stronger, methods of drilling to reach the deeper oil reserves. That is why BP launched the project 20K in early 2012. The project is a multipronged research and development program to "develop, by the end of the decade, the technologies to be able to drill, complete, produce, and intervene in deep water reservoirs that have pressures of 20,000 psi at the mudline," defined by BP's Project 20K leader, Kevin Kennelly [4]. The system will be able to access an estimated additional 10 to 20 billion barrels of oil over the next 20 years. Not only will the system have to withstand 20,000 psi in pressure but also 350°F temperature. Much of the design work for this new system includes the development of components and processes that are not available today. The new components must be much stronger than before, which poses as a dilemma for BP. They can either make the components such as the casings and drilling pipes larger, or they can use lighter, stronger materials to increase the strength of these components without increasing the weight. The whole idea is to increase the strength of the parts without increasing the weight because if the weight of the components increase then the hook at the surface on the platform must pull a much larger weight and must be much stronger. The hook load on the new vessel could reach three million pounds whereas the current capacity is 2.5 million pounds [4]. That would result in a larger crane and platform or a completely different and new crane and platform design.

Currently the thinking in the 20K project maybe to switch to a ship-like hull design, for the drilling platform instead of going in their current direction, which was the massive 75,000 metric ton semisubmersible platform named Thunderhorse. It can process up to 250,000 barrels of oil each day. For reference, Mad Dog has only 21,000 metric tons and can produce only 80,000 barrels of oil each day [5]. The reason for selecting the ship-based rig is because one can get more payloads onto a drillship than a semisubmersible for the same cost. Also, the 20K project will require the oil to be processed on floor before being pumped up to the surface because of the high pressures and immense distance the oil needs to travel, almost 2 miles vertically. In order to process the oil at depth a new high-integrity pressure protection system (HIPPS) needs to be designed. This has been contracted out to FMC Technologies and will be explained later. HIPPS is basically a valve that closes when it senses a rise in pressure so that smaller diameter tubing can be used after it to save weight and cost. If HIPPS was not there, the small diameter tubing would rupture if the pressure rose significantly like the shut-in pressure of the well [4]. Other new and updated component systems will include the BOP, wellhead, and active monitoring systems for safety just to name a few. The new BOP is estimated to weigh 50 percent more than the original 15,000 psi BOP, to accommodate the immense forces at the extreme depths and especially the extreme temperatures. The valves in the BOP are made of materials that cannot cope with the new higher temperatures and thus need to be redesigned, rethought, or enhanced. With the demand for oil increasing, and the possible 10 to 20 billion extra barrels of oil available for the taking, the future of ultra-deep-sea oil drilling rests in the 20,000-psi class and Project 20K will pave the way with new technologies to cope with the high pressures and high temperatures.

7.2.1 HIPPS

The HIPPS is a huge asset in the cost of materials and operation in deep sea oil drilling. Because of the extreme pressures at the bottom of the sea, the equipment and specifically the pipes used to bring the oil to the surface have to be highly fortified to withstand the pressures if production is closed upstream of the unit. However, under normal operating conditions when the oil is being processed and able to flow freely, the pressures are immensely less. It is only when the valve is shut topside and oil flow stops that the pressures build. When this occurs, the pressure in the pipes up to the shut valve increases until it reaches equilibrium pressure that occurs at the oil field. This pressure can be in the order of 20,000 psi. Instead of designing the entire riser system and pipes to withstand that pressure, a HIPPS is used to act as a valve and stop the flow of oil and thus the increase in pressure at the well head. This means that after the HIPPS unit the pipes only need to withstand the normal operating pressures. Thus, the wall thickness can be reduced by about 30 percent [6]. When taking into consideration the miles of piping needed to reach topside, the savings are immense. For a 19-mile long, 12-in. tie-back at 10,000 psi the savings in pipeline cost with the subsea HIPPS could be in the order of $25 million [6]. In the case of the new chapter of oil exploration where pressures are around 20,000 psi, the savings can be substantially more. That is why there is such a high demand for these units. Currently, there are no HIPPSs that perform under the 20,000 psi and 350°F conditions. Therefore, new testing and design must take place. The system is designed to use a fail-safe functionality, which means that if there is a failure, the system will automatically close, and the valves are kept open only by an applied hydraulic pressure. The system uses a two out of three voting scheme in order to improve reliability while reducing the amount of misfires due to anomaly readings. The pressure is measured using a strain gauge to convert pressure to electrical input that can be processed by a computer. The three values for the pressure are taken and if two of the values are above the critical pressure, then the system stops sending power to the valve solenoids. When the solenoid is energized, the hydraulic valve feeds fluid to the barrier valve actuator to open the pipeline: loss of solenoid power makes the barrier valve close [6]. The barrier valve is a metal-to-metal seal with elastomer backup on the seat to body and stem seals [6]. This elastomer is one of the critical components that do not stand up to high temperatures. Currently, the original elastomer will not work in the 350° condition and thus new studies and research are being conducted to find a replacement for it in the next generation of 20,000 psi HIPPS. In addition, in Figure 7.1, an example of a system of a subsea oil platform is shown for reference. Here, there are four well heads connected to two different HIPPS units that can be seen in orange gray. These units monitor the pressures at the well heads and shut off the flow if a pressure rise above the critical pressure is measured. This way the high pressures are contained to just the well heads.

There is also a multitude of simulation data that are used in the process of designing these HIPPS. The model simulations were all done at a maximum operation range in the 15,000 psi category. Now with the higher pressures and temperatures, the fluid flow, pressure buildup, and

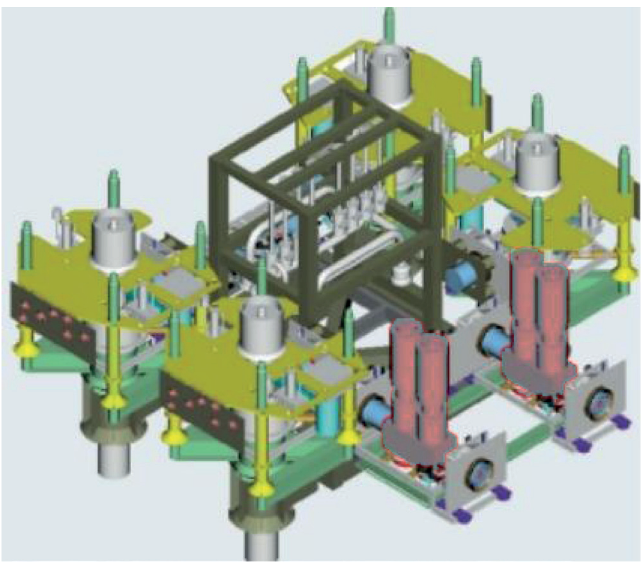

Figure 7.1. A subsea oil platform with four separate well heads and two HIPPS in orange gray [6].

safety design all need to be remodeled and simulated again. For example, under the lighter loads, it was calculated that when a higher pressure is measured above the critical pressure, it takes approximately two seconds for the system to recognize and finish closing the valves. This means that the tubes need to be fortified a distance equal to the amount the high-pressure oil will travel. Now with higher pressures, the oil will travel that much further requiring a longer fortified region of tubing before the tubing can drop down to the smaller operational thickness. HIPPS units are thus extremely necessary in ultra-deep-sea oil drilling and must be updated and improved for the future 20,000 psi standards.

7.2.2 BOP

BOPs are effectively a massive system of valves measuring over 60 ft. in height and weighing several hundred thousand pounds. Their main job is to isolate the massive pressures that can occur while drilling in deep sea oil wells [7–9].

The BOP is one of the most critical safety devices in the entire drilling system. The BP oil spill in the Gulf of Mexico was caused by multiple failures in the BOP. The failure allowed gas and oil to reach top-side at an uncontrollable rate and thus flooded the engines and resulted in a blackout of power on the oil rig platform. The blackout disabled the dynamic positioning system that used GPS to keep the rig directly over the well and thus the rig started to move off the well site. This caused the fracture of the drill tube and resulted in massive explosions on the drill deck and the inevitable sinking of the oil rig. The result was massive economic losses and a national environmental disaster with the spilled oil. All of this was due to the failures in the BOP. That BOP was rated to 15,000 psi, and now companies are trying to advance to the 20,000 psi benchmark. GE is one of the companies that is taking on this daunting challenge. GE Oil and Gas Drilling Systems must completely reengineer all the components in the existing 15,000 psi BOP to be able to cope with the immensely more demanding temperatures and pressures. GE also plans on developing several new techniques and technologies throughout the journey [7]. Some of the new key features that the 20-ksi system will have are an upgraded GE Ram and annular BOPs that will be designed for the specific demands of containing the high pressures and temperatures; GE's Sea ONYX, which is a control system designed to provide maximum system uptime; and finally GE's SeaLytics BOP Advisor Software, which is designed to provide real-time performance and maintenance data to reduce maintenance and to ensure a high margin of safety [7]. Therefore, not only do the mechanical components need to be updated but the software and control systems need to be updated as well. A new technology that we will most likely see in the 20K programs is the use of the risers, tubes that connect the platform to the BOP, as a pathway for data travel from the seafloor to the platform using inverters at each of the riser joints. This new ability to obtain real-time data of what is exactly occurring miles below the surface is critical to detecting a blowout before it is too late. Currently, the typical design of a BOP tower includes multiple variable bore rams at the bottom of the tower, a shear ram, and an annular or multiple annular at the top of the unit.

The role of the variable bore rams is to contain the pressure by forcing the ram around the circumference of the drill pipe and using its rubber seals to contain the high pressures and temperatures. The next line of defense if that does not solve the problem is the shear rams. These are crucial to the safety of the environment and oil rig topside. The two separate metallic pieces act as scissors to cut the drill tube and lock together to contain the pressures. There are rings which are the rubber seals that are designed to seal off the flow. Lastly, at the top of the BOP is the upper and lower annular. An example of an annular can be seen in Figure 7.2. The way an annular works is when it needs to close around the drill pipe the closing chamber fills with hydraulic fluid forcing the contractor piston up against

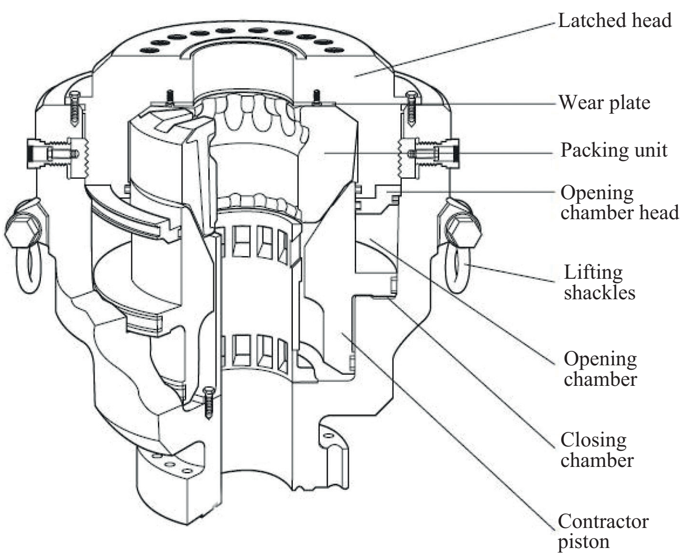

Figure 7.2. An annular ram cutout in a BOP [8].

the packing unit squeezing the unit inward and forcing it to seal around the drill pipe. All of these subsystems work together to prevent blowout, high pressure, temperature oil and gas from reaching topside or rupturing other key equipment. This entire system needs to be meticulously updated from the ground up for the pressures at 20,000 psi because if it is done wrongly a failure could mean catastrophic losses to the environment, human losses, and economic losses.

7.2.3 LOSAL EOR

Once the well has been drilled all the way to the oil reservoir, it is time to start collecting oil. Using traditional methods, only 10 percent of the oil can be obtained because most is left chemically or physically bonded to the rocks and sediments. This is where new technologies have come into play. Currently, companies all around the world are using salt water to help free the oil from these crevices. However, this method extracts an average of 35 percent of the oil in the reserve. The problem that has been haunting oil companies is that a large majority of oil is left chemically bonded to the sediment like clay [10]. This is why companies like GE have invested in looking at the chemical properties and chemical bonds that prevent oil from flowing out of the oil field. Chemical studies have revealed that oil molecules are chemically bonded to clay particles by bridges of divalent cations such as calcium and magnesium. These cations are compressed on the clay by electrical forces when exposed to high-salinity water [10]. That is why there is a need to lower the salinity level of the water being used so that the forces are reduced and the chemical bonds can be replaced with monovalent ions such as sodium. This would allow the oil molecules to be freed and swept up the well. Originally, the idea of using low-salinity water to flush oil out was thought to be crazy. The oil industry says that one should never use low-salinity water because it will be soaked up by the clay particles and cause them to swell. This swelling closes gaps the oil might have had to escape. However, the process of low-salinity-enhanced oil recovery (LoSal EOR) has proven to be a huge leap forward in the field of oil production. The LoSal EOR process was first tested in the Endicott oil field in Alaska. As a result, the process was introduced to offshore fields. Now, as a result of these successful tests, BP has announced that it plans to use LoSal EOR for the first time on a large-scale offshore site, Clair Ridge. Located on the UK Continental Shelf, the £4.5 billion development plans on spending a wise $120 million on creating on-site water desalination facilities for the oil extraction [9]. This means that compared to conventional water flooding, BP estimates that it will contribute

42 million barrels of additional oil of the estimated 640 million barrels of recoverable oil at the site [10]. To put this into perspective, if BP increased its recovery rate by just 1 percent, it could yield an additional two billion barrels of oil equivalent [10]. The problem with this is finding ways to efficiently provide the equipment for desalination in current existing rigs. However, hopefully in the near future, the process will be an industry standard in the oil recovery technique.

7.3 DISCUSSION AND CONCLUSION

With the demand for oil rising at an alarming rate, oil companies are pushed to go to new extremes to tap in to the remaining oil fields. Much of these oil fields left are located miles below the surface of the ocean. Marine oil exploration started in the 1940s by drilling a well in just 15 ft. of water. The depth of the water has been a huge constraint for oil companies because of the massive pressures and temperatures experienced at these depths. Fast forward 70 years and the 15 ft. of water depth is shattered by a current industry standard of 15,000 psi, which is about 10,000 ft. below the surface of the ocean. New oil field discoveries and depleting accessible oil fields have forced them deeper and deeper over the years. Thus, technologies are forced to improve as well. Currently, the oil industry is at the cusp of the next generation of offshore oil production to have a standard of 20,000 psi and 350°F that will allow them to access oil at locations that have an ocean depth of 12,500 ft. BP calls its advancement into the next generation as Project 20K. This is an immensely challenging task not only in terms of mechanical engineering but also in terms of software and electrical engineering. With the higher pressures they previously used to go with the bigger, stronger, heavier motor. However, it has reached a point where the materials would need to be so large that the project would be unfeasible. Thus, BP and the rest of the large oil companies are forced to reengineer new methods, technologies, and control systems to update the current technologies for the huge physical demand at the high temperatures and pressures experienced at the new depths. One of these critical components is the HIPPS. The HIPPS is an extremely valuable device that separates the high pressures experienced in the well from the normal operating pressures in the pipelines downstream the HIPPS. However, with these higher pressures and temperatures come challenges in redesigning the HIPPS unit to operate safely and effectively. Similarly, the BOP unit sits on top of the well head and prevents similar high pressures from escaping the well under blowout conditions. These two units are crucial in providing safety to the crew on the oil rig and also crucial to the protection of the environment by preventing oil spills like the Gulf oil spill from BP. In fact, it was all due to multiple failures in the BOP. The need for new systems that can withstand the pressures and temperatures at 12,500 ft. below the surface is imperative. With the new process of LoSal EOR, oil wells can be even more effectively drained of their precious liquid. LoSal is a process of using low-salinity water to flood the oil field and force oil molecules free that were previously chemically bonded to clay molecules in the earth. It has the potential of producing 30 to 60 percent more oil than is possible using primary or secondary recovery techniques. This means that each oil field is that much more worth the cost in accessing it, and access it they will.

ACKNOWLEDGMENTS

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CHAPTER 8

Harvesting Geothermal Energy from Oil Wells and Other Unexpected Sources

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8.1 INTRODUCTION

In the coming decades, as the finite supply of nonrenewable energy (e.g., fossil fuels) dwindles, the world will increasingly be powered by renewable energy sources. One promising source is geothermal energy, in which heat trapped beneath the earth is used to generate electricity. Unfortunately, the cost to drill a geothermal well can account for up to 50 percent of the total budget of a geothermal project [1]. Therefore, there has been much interest in using abandoned oil wells as sites for the construction of geothermal power plants, a technique that would obviously mitigate the initial cost for getting such an operation running.

The United States stands to benefit immensely from increased geothermal power generation, due to the economic boon of investment in alternative energy, the reduction of our dependence on foreign sources of energy, and the health benefits associated with fewer pollutants in the atmosphere. This chapter will explore the current designs being researched to utilize spent oil wells for geothermal energy production, how such designs may perform in the field, as well as explore other methods to harvest geothermal power from oil well infrastructure. It will also give pause to consider the potential drawbacks of reactivating oil wells that have been out of use for a long time. Given the number of active, retired, and abandoned oil wells in the United States, which number in millions, recommendations of specific sites to implement innovative geothermal technologies will not be given, but more general suggestions, that is, providing facts for a certain region of the country, may be included.

8.2 GEOTHERMAL ENERGY

Geothermal energy is a result of the temperature gradient between the core of the earth, which has never been observed directly, but has been theorized to exhibit temperatures of approximately 10,000°F, and the much cooler crust, with temperatures around 750°F. Because of this large difference, thermal energy constantly radiates outward to earth's surface, making it more accessible [2]. Also, because of earth's molten mantle, convection effects occur that also transfer heat to the surface. The molten mantle is also the mechanism behind plate tectonics. Since geothermal energy is only dependent on the heat of the earth, it possesses a distinct advantage over other renewable resources, such as wind or solar energy, in that it is always available and will not be affected by still air, inclement weather, or night.

One common method to convert geothermal energy into electricity is to pump water into a geothermal well to increase its temperature, retrieve the hot water to drive a steam turbine connected to a generator, and then reuse the cold water to repeat the cycle. This is similar to the operation of other power plants, the crucial difference being that the water is heated using the earth instead of by burning fuel, which greatly reduces the environmental impact of such a power plant. Typically, the only fuel consumed in the daily operation of a geothermal power plant is the fuel used to power the pumps that drive the water underground. The general name for this method is hot fractures rock (HFR) [3].

The second way to harvest geothermal energy is known as "wet" geothermal. It is only feasible where steam or superheated water exists close to the surface because of nearby volcanism or another is heated by other natural means. An example of wet geothermal energy being harvested is from New Zealand in the countryside near Auckland [4]. They retrieve the hot water from the ground, transfer its thermal energy to separate water in a closed system using a heat exchanger, and use it to drive a steam turbine. Figure 8.1 depicts the difference between the HFR and the wet geothermal methods.

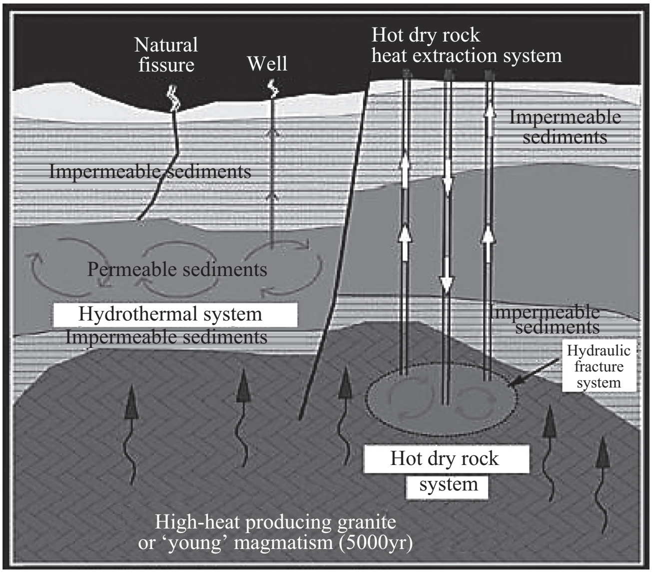

Figure 8.1. A comparison of the dry and the wet geothermal systems [5].

Obviously, there may be multiple closed-loop systems of water at work, that is, the water pumped underground may not be the same water used in the turbine. If this is the case, there will be heat transfer between the systems of water. There are three major types of geothermal power plant cycles currently used. The selection of one of the three main methods is dependent on the geothermal fluid used and its temperature. The first, and oldest, is the dry steam power plant. It is arguably also the simplest method, in that steam taken from the ground travels directly to a turbine, which in turn powers a generator to store electricity. The emissions of such a plant are only excess steam and minor amounts of gas. This cycle is currently being used at the geysers, located in northern California, which is to date the largest singular source of geothermal power in the world [6]. Figure 8.2 shows a simplified schematic of a dry steam power plant.

The second method employed is known as the flash steam power plant. It is the most common kind of geothermal power plant currently in operation. Liquid water at high pressure and temperature (typically at or greater than 360°F) is pumped into a container at a much lower pressure. This causes the water to vaporize extremely quickly, or "flash." It is for this reason that the container is called a "flash tank." The vapor then drives a turbine. It is

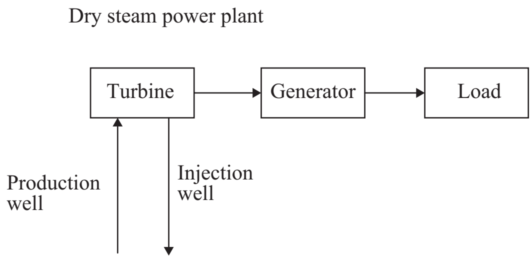

Figure 8.2. A diagram of a dry steam system geothermal power plant [7].

possible to have multiple flash tanks connected in series to reflash any liquid remaining from previous flashes in order to harness more energy from the liquid, of course, with diminishing returns for each successive flash.

The third method is called a binary-cycle power plant. It is considerably from the dry steam and flash steam power plant in that the fluid injected into the ground never comes into contact with the turbine. Instead, the geothermal fluid, which is typically below 400°F, trades thermal energy with the working fluid via a heat exchanger. This working fluid, the second in the "binary" cycle, usually has a much lower boiling point than that of water; hence, it changes to steam more easily and can generate electricity at a lower temperature. The working fluid is a closed-loop system, so there are no emissions to the atmosphere except excess water vapor from the heat exchanger. Figure 8.3 displays a design of a binary-cycle power plant. Most of the world's resources of geothermal energy, at least the ones humans can currently access easily, are below this threshold of 400°F, so one can expect most future geothermal power plants to be of the binary-cycle type [6].

One of the major limitations of geothermal energy, then, is clearly one of geography. The necessary geothermal energy required to construct a plant of any significant size is only available near areas of volcanic activity, on the borders of tectonic plates, or in locations of preexisting geothermal vents [2, 8]. Otherwise, one would have to drill extremely deep into the earth's crust before finding a usable source of heat. However, the proposed utilization of abandoned oil wells may help to solve this issue, as the initial drilling, presumably the most difficult and expensive step, has already been performed. In addition, the existing infrastructure at the well will lower costs further, making this sort of venture attractive to potential investors. It will also give value to the existing infrastructure, which would otherwise just sit unused, and reduce the environmental impact of starting at another geothermal site "from scratch," so to speak.

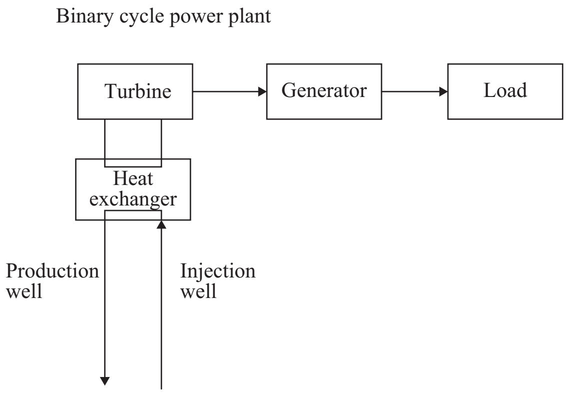

Figure 8.3. A binary-cycle power plant block diagram [7].

8.2.1 PROCURING GEOTHERMAL ENERGY FROM ABANDONED OIL WELLS

The design proposed by Bu, Ma, and Li involves sealing the bottom of an existing oil well with an insulating material, and then placing a long, dual-channel concentric pipe into the ground [1]. The outer pipe will inject fluid down through the surface of the earth, which will experience heat transfer with the surrounding hot rocks. Once it reaches the bottom, the heated fluid will return to the surface through the heavily insulated inner pipe. Figure 8.4 shows the diagram of the pipe with fluid flow outlined.

The calculations performed demonstrated that the temperature of the extracted fluid would be 266°F, and would drop to 262°F after 10 years of being in operation [1]. This assumes, among other things, a geothermal gradient of 45°C/km, or 130.4°F/mile. This is a viable temperature range for the use of binary-cycle power plants with this apparatus. In their case study, the inner diameter of the pipe was 0.1 m, the outer diameter was 0.3 m, and the length was 4,000 m. The parameters yielded a net power output of 53.7 kW. However, this number is highly dependent on several factors, including flow rate, temperature of the rocks, and volume of the fluid. Some have suggested that 2 to 3 MW may be harvested from a single well [9].

8.2.2 PROCURING GEOTHERMAL ENERGY FROM OPERATIONAL OIL WELLS

In addition to using abandoned oil wells for geothermal energy, there is a strong incentive to use oil wells still in operation to produce electricity from

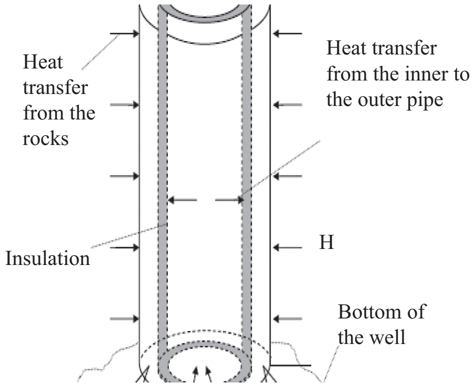

Figure 8.4. A figure of the concentric pipes designed for use at an abandoned oil well for geothermal power generation [9].

geothermal energy. Hot wastewater is a by-product of oil wells throughout the United States, which produce 25 billion barrels of this water annually [10]. Instead of being dealt with as a waste, this water is now being treated as a resource to exploit for further electricity generation. The water would take the place of the primary fluid in the binary-cycle power plant previously described. The U.S. Department of Energy estimates that there are 823,000 oil and gas wells that produce hot wastewater in the United States. These sites, if they make use of the water to create geothermal energy, could produce an additional 3 GW of power annually [11]. Also, this technology can be scaled to different power outputs based on the size of the geothermal resource and the demand for power. At the Rocky Mountain Oilfield Testing Center at the Teapot Dome oilfield in Wyoming, a binary-cycle geothermal power plant is currently online, which has successfully validated the principle of using coproduced fluid. It is capable of producing 200 kW of electricity.

A good place where coproduced resource power plants could be implemented is Texas. It is home to an extensive number of oil wells, as well as geothermal energy. It is estimated by Southern Methodist University that there is 921 exajoules (exa- = 10^{18}) in the existing network, with about 2 to 10 percent of that figure able to be recovered [12]. Also, these power plants could be utilized to give power to the oil well operation itself instead of being connected to the electricity grid. This would realize lower production costs, and the average American would benefit from less expensive domestic oil as well as the added resource of renewable energy in the form of geothermal energy.

8.2.3 GEOTHERMAL ENERGY FROM HYDROTHERMAL VENTS AND OFFSHORE OIL WELLS

Another large untapped source of geothermal energy does not lie underground, but under the sea. Hydrothermal vents, which run along the seafloor and eject water at superheated temperatures of over 800°F, are another potential source that could be used to power our world. The water stays in its liquid form because of the immense pressure at that depth. Also, the pressure is the mechanism that forces the water down through the fissures to the magma, which heats it up and then recirculates to the seabed.

There are a number of potential issues that arise with harvesting geothermal energy from the depths. First, the hot water needs to reach the surface, which is usually more than a mile up at the locations of most geothermal vents. The pipes that drive the water to the surface will have to be well insulated to ensure that the surrounding cold water does not decrease the temperature of the water to the point of being unusable. Also, 800°F is hot enough to melt lead, so issues with containing the hot water may also arise.

In addition to being a source of geothermal energy, these vents are also home to rich deposits of minerals. When the water is ejected from the earth, it takes with it tiny particles of metals which resembles smoke as it exits the vent, and then rests on the seabed like a fine snow. The metals found have included gold, silver, and copper, often found in concentrations much higher than those in mines on land [13]. This potential for precious metals could help secure funding to construct the infrastructure necessary to reach the bottom of the ocean and harvest the energy it provides. Also, much of the existing technology used in offshore oil drilling platforms could be tailored to retrieve water instead of oil. Indeed, existing platforms where oil is no longer present have the possibility of being used to drill for deposits of hot rock underground. In other words, we could potentially create hydrothermal vents where none currently exist.

The Marshall Hydrothermal Recovery System is one proposal for turning theoretical geothermal energy into a reality. Their system essentially caps the vents and the water is taken to the surface through a combination of convection, flash steam pressure, conduction, and flow velocity [14]. The system employs the use of cold seawater, taken just beyond the depth where sunlight can penetrate, to be the cold side of the heat reaction, since the energy yield from a thermodynamic cycle is proportional to the magnitude of the difference in temperature between the two working fluids. Presumably, the power plant itself will be a binary-cycle power plant, as seawater is highly corrosive and it is desirable to keep it separate from delicate machinery such as turbines. The cold seawater will be delivered using a "thermal enhancement pump." The Marshall Hydrothermal Recovery System also has designs to extract the valuable minerals from the seawater it takes in, as well as plans for water desalinization. As stated before, some of the superheated water will turn to steam as the pressure decreases, and this steam will be condensed into fresh water. Per Marshall hydrothermal's estimate, their system would pump 20 million gallons of water to the surface hourly, so even a small fraction of this would yield a considerable amount of potable water [15].

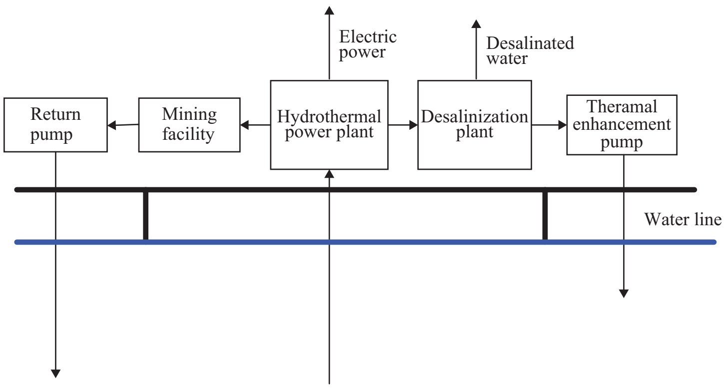

Figure 8.5a. The Marshall Hydrothermal Recovery System, shown with a power plant, mining facility, and desalinization plant [16].

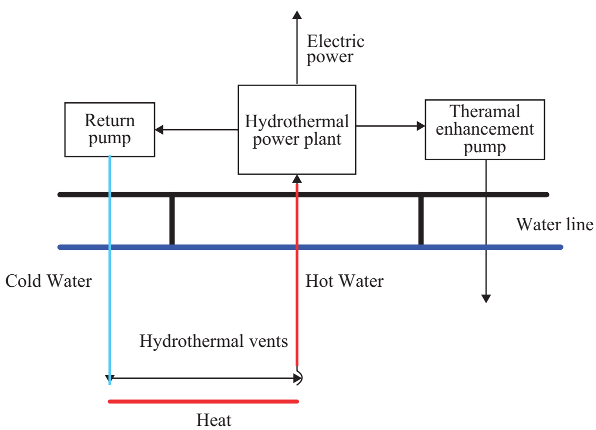

Figure 8.5b. The closed-loop version of the Marshall Hydrothermal Recovery System with a working fluid different from salt water [16].

There is also development toward a closed-loop system where water closer to the surface would be pumped to the depths and exposed to the heat of the vent. This approach is much less invasive to the vent itself and would not disrupt the exotic life forms that call hydrothermal vents home. It also may prove more practical to use this method at dry offshore wells, as the heat from the crust will still be present but a large vent may not be. Figures 8.5a and b show the full Marshall Hydrothermal Recovery System, including mineral extractor and desalinization plant, and the closed-loop system, respectively.

8.3 ISSUES WITH GREENHOUSE GASES

There is no debating the danger of excessive greenhouse gases (GHGs) released into our atmosphere. They can cause adverse effects on multiple aspects of the environment, including rising sea levels and diminishing air quality. There is even research that suggests inhalation of carbon dioxide and other GHGs can cause increased appetite and a feeling of lethargy in humans [17]. Therefore, a recent study that has found that abandoned and plugged oil wells are releasing methane gas, another GHG, into the atmosphere deserves attention. Mary Kang of Princeton University surveyed 19 oil wells in the state of Pennsylvania and discovered that they were leaking methane at various rates. The amount per oil well is small, but there are hundreds of thousands of abandoned oil wells in Pennsylvania alone. Kang extrapolated that if all such wells were leaking methane at a similar rate, it would account for 4 to 13 percent of methane emissions in the state as a result of human activity [18].

These findings should weigh on anyone who wishes to consider abandoned oil wells for geothermal power generation. Unplugging or uncapping an oil well, as well as using one that was simply abandoned, has the potential to release a significant amount of methane or other GHGs at one time that would otherwise remain trapped or be released slowly. Outfitting the well with the necessary equipment also runs the risk of disturbing pockets of harmful gas trapped underground. Steps should be taken to ensure that there is little to no such risk of a major release of gas, and sequestration could be considered if there is a release. Given the number of abandoned oil wells nationwide, it would be preferable to select a location where this is not an issue, but if current technology for detecting underground gas pockets is not sophisticated enough to reliably indicate them, then that is not feasible. Also, remaining methane may be an inevitability of abandoned oil wells.

8.4 CONCLUSION

There is a pressing need for society to revolutionize how it satiates its ever-increasing appetite for energy. A promising source in the coming decades is geothermal energy. As previously stated, it possesses advantages over other renewable sources in that it is always available to harness, replenished by the heat from the core of the earth itself. However, as we have seen, this thermal energy is not always readily accessible. With abandoned oil wells, a large supply of water or another working fluid will have to be introduced to receive the heat from the hot rocks. With operational oil wells, the geothermal energy coproduced from the hot wastewater is dependent upon the processes that retrieve and produce oil, which introduces some ambiguity into the question of whether geothermal energy from this source is truly "clean energy." As for hydrothermal vents, the technology needed to reach the ocean floor with such an apparatus described may not be available in the immediate future, but the energy density of the superheated water at those depths, as well as the windfall from the mineral deposits located near the vents, should incentivize researchers and corporations alike to invest in developing the technology needed. Regardless of how it is harvested, geothermal energy is a promising source of power for mankind's future, due to its scalability, availability, and the fact that its power cycle generates virtually zero emissions, except for the very thing that it consumed, water.

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CHAPTER 9

Nanotechnology in the Energy Industry

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9.1 INTRODUCTION

The need for alternate clean sources of energy has been a topic of interest for many decades. Even with the technology that is in use today, this issue has yet to be solved. Fortunately though, nanotechnology may be the beginning of this solution. Nanotechnology is a broad term typically used to describe materials and phenomena at the nanoscale (on the scale of one billionth to several tens of billionths of a meter).

Properties at these atomic levels are completely different from those of the material as a whole. This implies that with precise manipulation of the atoms and molecules of a material, custom-made substances with capabilities not found in nature can be produced. This makes the possibilities of nanotech in the energy industry almost limitless.

An evaluative bibliometric approach was taken by Menendez-Manjon and her colleagues to track the uses of nanotech from 2000 to 2009 [1]. By analyzing hundreds of articles and publications written between these times, they were able to see in which fields nanotechnology was most researched and experimented on. These fields include nanotech in energy harvesting (fuels, solar, wind, etc.), storage (batteries, supercondensers, etc.), conversion (photovoltaic [PV] cells, fuel cells, etc.), usage (thermal isolation, efficient illumination, etc.), and distribution (high-temperature superconductors and the like). There was a huge peak in 2003 in publications for energy harvesting. However, there are a lot more publications for nanotech in energy conversion than for any other field. Despite this research, nanotechnology has been most applied to energy harvesting. Energy harvesting, storage, and usage make up over 90 percent of the applications of nanotech from 2000 to 2009. This study will focus on the advancements in these fields.

9.2 ENERGY HARVESTING AND CONVERSION

Energy harvesting and conversion go hand in hand, so they will be discussed together. All elementary steps in energy conversion (charge transfer, molecular rearrangements, and chemical reactions) occur at the nanoscale. Thus, manipulation of objects at this scale can vastly improve them both physically and chemically. Nanomaterials can be produced in a variety of material classes such as carbon-based nanomaterials, nanocomposites, metals and alloys, biological materials, nanopolymers, nanoglasses, and nanoceramics [2]. These nanomaterials have appealing properties that can make them more efficient than their natural counterparts. An example of this is that the very high surface area per unit volume of nanomaterials leads to a higher surface activity. This, in turn, speeds up chemical reactions and catalysis, which improves the efficiency and cost of many systems [2]. The most popular applications for nanotech in the field of energy conversion are on solar energy and hydrogen conversion and storage.

9.2.1 SOLAR ENERGY (PV TECHNOLOGIES)

The sun provides an almost limitless amount of free energy. In just one year, it can provide the earth with 15,000 times more energy than the atomic and fuel energy actually needed during the year [3]. Some of the ways that this abundant energy has been partially harvested and converted include PV technology—which directly converts light into electrical, solar-thermal systems—which are used in solar collectors, artificial photosynthesis—which through water splitting produces either carbohydrates or hydrogen, and even biomass technology—where plants use the solar radiation to drive chemical transformations to create complex carbohydrates, which are used to produce electricity, steam, or biofuels [3]. PV technologies will be focused on as they offer a low energy density as well as a conversion efficiency and have the most to benefit from the incorporation of nanomaterials.

A PV cell consists of a diode made of a semiconducting material sandwiched between two electrical contact layers [2]. They produce electricity from the sun's radiation by converting the photons from light into electrical energy. There have been three generations of PV technology so far. The first generation uses silicon wafer–based solar cells, which are thick cells of around 150 to 300 nm and made of crystalline silicon. This accounts for more than 86 percent of the global solar market [3]. The second generation of PV materials uses thin film layers of semiconductor materials. These cells make up 90 percent of the market space but only a small percentage of the global PV market. Although they do offer lower manufacturing costs, this lack of popularity is probably due to its low conversion efficiencies. Using nanoscale components can help this generation in two ways: (1) by manipulating the energy bandgap, which allows for flexibility and interchangeability and (2) by enhancing the effective optical path, which significantly decreases the probability of charge recombination [3]. The bandgap of a semiconductor is the minimum energy needed for an electron to free itself from the semiconductor surface and participate in conduction. The third generation of PV materials involves the use of nanocrystal quantum dots. These dots are nanoparticles usually made of direct bandgap semiconductors and lead to thin-film solar cells based on silicon or conductive transparent oxide with a coating of nanocrystals. Quantum dots are efficient light emitters because they are capable of emitting multiple electrons per solar proton, with different absorption and emission spectra depending on the particle size, thus raising the theoretical efficiency limit by adapting the incoming light spectrum [3]. This generation is still being developed, but with efficiencies close to 40 percent, quantum dots have a promising future in the line of solar cells.

The newest generation of PV materials, or composite PV technologies, mixes conductive polymers or mesoporous metal oxides with high surface areas to increase internal reflections with nanoparticles to make a single multispectrum layer. Theoretical efficiencies of up to 86.5 percent can be accomplished; however, these efficiencies are yet to be achieved in practice [3]. This generation is still very early in its stage and has much development to come.

Even though the sun offers free energy, PV technology represents only 0.04 percent of the world's total primary energy supply. This is not to say there has not been any advancement. Growth in research and development of this technology has led to price falls in the last 20 years (2.00$/kWh in 1980 to 0.20 to 0.30$/kWh). It is estimated that prices will continue to fall to around 0.06$/kWh by 2020 [3]. In order for PV technologies to become more widely used, they need to significantly increase their efficiency–cost ratio. This can be accomplished by incorporating nanomaterials such as quantum dots. With its increasing popularity, there will continue to be vast improvements in both efficiency and price of PV technologies.

9.2.2 HYDROGEN CONVERSION AND STORAGE

Hydrogen is a great energy carrier because its combustion only produces water—no greenhouse gases [2, 4]. It also is a way to transport and store energy from its sources to the end user. While the main renewable energies such as solar, wind, geothermal, or tidal need to be transformed into electricity, hydrogen needs only to be produced. However, since hydrogen is a vector and not a source, it is as clean as the method used to produce it [3]. While there are various ways to produce hydrogen, there are few ways that do so with no pollution. Water splitting is a broad term used to describe any process in which water is broken into hydrogen and oxygen. PV energy is one way of water splitting that can be used to break water molecules into hydrogen and oxygen (via photocatalytic water electrolysis). This means that solar energy can theoretically be directly stored in the form of hydrogen with little to no pollution. Nanotech is currently being used to try and produce hydrogen from solar energy in a cost-effective way. Titanium oxide (TiO_2) has largely been looked into since, as a catalyst, it offers a clean and cheap way of combining hydrogen and oxygen into water [5]. The drawback is that only UV light can be used since its bandgap is around 3.2 eV. Research is ongoing in treating these drawbacks in the nanoparticles of TiO_2.

One of hydrogen's biggest drawbacks is that current hydrogen storage systems are inefficient. Since this gas has a high calorific value by mass but low calorific value by volume, it needs to be compressed in order for it to be stored and used [2]. Pressure vessels for this compressed gas tend to be bulky and heavy. Hydrogen can also be stored as a liquid fuel, but this requires very low temperatures [2]. Currently, hydrogen absorption is considered to be one of the most efficient ways to store this gas [3]. The main drawback in current methods is that their pores tend to be larger than hydrogen atoms or molecules themselves. By reducing the size of the absorbing material to the nanoscale, hydrogen absorption can be improved. As an example, mesoporous materials exhibit controlled pore size and large surface areas. Through this method of using nanomaterials, high hydrogen absorption capacities can be obtained by manipulating surface area, pore size and shape, storage capacity, controlled desorption, and safety of these materials [3].

9.3 ENERGY STORAGE

Various methods of electricity production have been looked into so far. However, once this energy is produced, it has to be stored somewhere. The two most important energy storage systems are batteries and electrochemical capacitors (ECs). Batteries store electrical energy chemically whereas capacitors store electricity physically be separating the positive and negative charges. Carbon nanostructures can be applied in energy storage as electrodes in electrochemical devices due to their large surface area and high electron conductivity [6]. This is just one among the many ways in which nanotech has developed these storage systems.

9.3.1 BATTERIES

Batteries have a multitude of applications ranging from cars to microchips. All batteries are made up of two electrodes that are connected by electrolytes, or ionically conductive materials. The energy output is a function of the cell voltage and capacity, which is also dependent on the chemical properties of the cells in the battery. Thus, the three ways to maximize the stored energy of a battery is by (1) having a large chemical potential difference between the two electrodes; (2) making the mass or volume of the reactants per electron as minimal as possible; and (3) ensuring that the electrolyte is not consumed in the chemistry of the battery [7]. Nanotech has been slow in entering this field. It was not until recently (2000) that it was realized that unwanted reactions could be solved by coating the electrodes in nanomaterials. Most research in this field of combining nanoscience with batteries has been dedicated to rechargeable lithium (Li-ion) batteries [6]. Some drawbacks to these batteries are its low energy and power density, large volume change on reaction, safety, and costs [3]. Such electrode kinetic issues can be helped by using carbon “nano-painting” [7]. This shortens the diffusion path for ions and electrons and can help raise the energy and power density. In terms of the volume change, by accommodating the strains as a result of Li reactions, nanomaterials can even be used as the volume changes upon reaction. However, one of the most important shortcomings in electrodes based on nanomaterials is the poor packing density. This limits the amount of energy that can be stored per unit volume or mass [7].

Solid electrolytes have also benefited from the use of nanomaterials. The addition of “nano-fillers,” or nanograins dispersed in a polymer, in polyether-based electrolytes increases the conductivity manifold at 60°C to 80°C [7]. However, there are no advantages at room temperature (20°C to 26°C). This can be helped by organizing the polymer strands in a way to locally increase order (i.e., crystalline stretching). This will allow for an increased conductivity at lower temperatures.

More generally, nanomaterials also have the advantage of changing the reaction pathway within the battery cell. As a result of this, high capacities and rechargeability can be added to a range of battery systems. An example of this is called conversion from transition-metal oxides where the final product is a homogeneous distribution of metal nanoparticles [7]. The drawback to this is its poor energy efficiency as a result of the large voltage difference between charge and discharge. This problem is still being addressed.

9.3.2 CAPACITORS

Since the discovery of capacitors, these devices have generally been getting less attention than batteries do. However, with the advancements in nanotechnology, these storage systems have been getting more attention and thus have recently been researched more. The three main drawbacks of traditional capacitors are: (1) the high cost of premium performance electrodes due to the miniaturization; (2) the large requirements for life cycles around 10^5 cycles; and (3) their low efficiencies [8]. Surface area is an important factor in determining power density and maximum power output. Nanostructured materials can significantly increase this area [3]. However, cheaper ways to minimize the capacitors while increasing their life cycle are still being looked into.

Three types of ECs exist so far: (1) pseudocapacitors, or redox supercapacitors, (2) electrochemical double layer capacitors (EDLCs), and (3) hybrid capacitors. The nanomaterials typically used are metal-based nanocomposites and conductive polymers, carbon-based nanostructures, and hybrid inorganic/organic nanocomposites, respectively [3].

Currently, the most common devices are the EDLCs. These devices involve blending porous materials (i.e., activated carbon) with a conductive additive (i.e., metals). By incorporating carbon-based nanostructures rather than activated carbon, the performance of EDLCs can be improved. Both carbon nanotubes and nanofibers allow the solvated ions to easily access the interface of the double layer [3]. Thus, a higher specific power, specific capacitance, and conductivity can be attained by combining activated carbon with carbon nanotubes (or nanofibers).

Pseudocapacitors are similar to Li-ion batteries in that stored charge is directly proportional to the electrode surface [9]. So the same methods that were used to improve lithium batteries can also be used for redox capacitors. This includes methods such as the transition metal oxides that were discussed in the previous section.

Hybrid capacitors combine the technologies of both Li-ion batteries and EDLCs. Within these capacitors are a capacitive or pseudocapacitive electrodes, which act as a power source and a battery electrode, which acts as an energy source [1]. Both electrodes are in the same cell as an electrolyte, which could either be aqueous or organic. Nanotechnology has been able to make advancements in both electrodes, and as a result, the capacitor as a whole. For the capacitive electrode, carbon nanotubes can be used to increase its surface area. For the battery-like, or negative, electrode, there are two ways to improve them: (1) through the use of inorganic nanomaterials capable of lithium intercalation when coming into contact with water and (2) through the use of nanostructured metal oxides [3]. These additions have resulted in an increase of energy density; however, at the expense of cyclability [1].

9.4 CONCLUSION

Nanotechnology research and development in energy applications is a promising field. Between 2000 and 2009, 90 percent of this research was dedicated to energy harvesting, conversion, and storage. This increase in research of nanotech has led to breakthroughs in each of these fields. In terms of harvesting and conversion of solar energy into electrical energy, PV technology is becoming increasingly more efficient, clean, and cost friendly. The production and storage of hydrogen has also been helped with the use of mesoporous materials to increase storage size. In terms of energy storage, batteries and capacitors have both benefited thanks to the implementation of nanostructures that offer larger surface areas, thus more storage [10]. The materials of today cannot solve today's problems; however, with the advantage of being able to control size, structure, and organization of matter at the nanoscale, unique properties can be created in bulk materials to eventually solve these problems.

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CHAPTER 10

Offshore Wind Power and Related Immature Technologies

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10.1 INTRODUCTION

Renewable energy is today's biggest focus when it comes to energy production and the environment. This has led to developments in renewable energy, which is energy that meets the needs of the present without compromising the ability of future generations to meet their own needs without impacting the environment [1]. Tidal, geothermal, wave, solar, and wind energies are some examples of renewable energy.

This chapter will focus on wind energy, specifically offshore wind power. Covering its history, the different types and how they work, economic and environmental impact, public opinion, and the development of related immature technologies.

The term "offshore wind power" is for wind farms that are built over water to produce electricity. Offshore wind power also includes inshore bodies of water such as lakes, fjords, and sheltered coastal areas.

10.1.1 WHY A NEW SOURCE OF ENERGY?

In the 1950s and 1960s, oil was the world's major resource; however, it was predicted that the world's oil would be depleted because human consumption was immense and only bound to increase. A theory established about the depletion of oil was "peak oil" in 1956 [2]. In addition, in the 1970s, environmentalists were concerned about the effects of pollution from oil use, and also used the dependence on oil as a reason to push reform for renewable energy. This led to the initial electricity-generating wind turbines. At this point, solar energy had been used at a very basic level because solar farms were too expensive to build; however, that changed in the 1980s [3].

10.2 HISTORY

Using wind as a source of energy dates back to nearly 7,000 years when wind was harnessed in order to drive ships on the Nile [4].

NASA began harvesting wind energy, which is generating electricity from the wind, since the 1970s. It intended to predict wind turbine power generation during high winds [5]. The technology developed from wind farming on land, to farming on water because wind speeds are higher offshore, therefore offshore can supply greater amounts of electricity. The largest disadvantage of offshore wind farms contrasted to onshore wind farms is the highly elevated costs [6].

10.3 TODAY

At the current time, Europe is the world leader in offshore wind power, with Denmark leading and constructing the first offshore wind farm in 1991. Being a clean and reliable source of energy, the rest of Europe followed the way and, by January 2014, there were 69 offshore wind farms in Europe with a total rated capacity of 6.562 GW in 2013. Individual European country offshore wind farm capacities can be seen in Table 10.1.

There are predictions about European offshore wind farm capacity at 40 GW by 2020, which would be satisfying "4% of the European Union's demand of electricity" [8].

The United States and China have also developed their own offshore wind farms. According to May 2014 data, China's offshore wind power capacity was 565 MW. China has set targets of 5 GW offshore wind capacity by 2015 and 30 GW by 2020, which will make it the world leader in offshore wind power generation [9]. "By 2020 the World's offshore wind power capacity is expected to reach a total of 75 GW" [6].

Siemens Wind Power (German) and Vestas (Danish) are the world's largest wind turbine manufacturers. The two companies together have

Table 10.1. European countries' wind power capacities as of January 2014 [7]

Country	Wind power capacity, MW
United Kingdom	3,681
Denmark	1,271
Belgium	571
Germany	520
The Netherlands	247
Sweden	212
Finland	26
Ireland	25
Spain	5
Norway	2
Portugal	2

installed 80 percent of the world's offshore farms as of January 2014. Third is Senvion-REpower with 8 percent, followed by Bard with 6 percent. The offshore farms require operators, with the leaders being Dong Energy, Vattenfall and E.ON [6].

10.3.1 THE UNITED KINGDOM

According to Stratford [10], back in 2007, offshore wind power was not as matured as onshore wind power. At that time, majority of the existing offshore farms were located in northwest Europe, with Denmark leading the way, and other countries in various stages of building the farms. The offshore wind sector was only 2 percent of the total wind installation rate. Reasons for this were planning and constant delays, developer cost and return evaluations being timely and costly, manufacturers' technology lagging, and lead time for ordering turbines being at least two years. Furthermore, "the economic gap between capital costs, expected operational costs, and revenue remains too large and uncertain for substantial industry commitment. Some major operators have placed planned developments on hold" [10].

The UK government addressed these concerns by providing incentives to industry players by reforming their Renewables Obligation Certificates, which are designed to encourage generation of electricity from eligible renewable sources in the United Kingdom [11]. They essentially guarantee the offshore wind farm that their generated power will be bought by the government at an agreed-upon price. This prompted developers to focus on assessments and techniques, specifically "applying operability analysis techniques to assist in equipment selection, specification and operating process design" [10]. These techniques had proved successful in offshore oil and gas industries. In addition, it was known that these industries' offshore rigs' productivity was affected by "the operating capabilities of the support services as well as the interaction of all the various on-rig components"; therefore, the same method was applied to offshore wind farms by developers.

10.3.2 CHINA

The Chinese are currently overdependent on coal. They are making great efforts to move away from this and are using offshore wind energy because of its advantages of not taking up land resources and the high utilization rate [12].

Their capacity at the end of 2012 was 389.6 MW and they are planning to increase this to 5 GW by 2015 and 30 GW by 2020 [12].

The challenges the Chinese are facing include power transmission methods, harsh environments offshore, and the time taken due to bureaucracy of multiple sectors coordinating their efforts [12].

10.3.3 UNITED STATES

There were no offshore wind farms in the United States (2009 data). Onshore wind power at the time accounted for fewer than 2 percent of the nation's electricity supply. The Department of Energy (DOE) issued a report in 2008 stating that the United States was capable of producing 20 percent of its electricity from wind by 2030. This was taken one step further by the DOE when they released a work plan in 2010 of how to achieve 54 GW of offshore wind power by 2030 that would cost 7 to 9 cents per kilowatt-hour [7].

The U.S. government provided incentives by passing various laws and legislations. One example is that the U.S. House of Representatives passed a Renewable Energy Standard of 20 percent by 2020 in June 2009. As of 2010, this had yet to be approved by the Senate. In addition, The

American Recovery and Reinvestment Act of 2009 provided around $100 million to offshore wind research [7].

10.4 UTILIZATION

Offshore wind farms are the most common utilization of wind turbines, as combining many turbines greatly increases the capacity, and makes use of economies of scale in procuring the equipment so that the cost is lowered.

Europe is the leader in wind farm numbers and total capacity. In 2012, 53 offshore wind farms existed in Europe [13].

In terms of capacity, the United Kingdom has the largest wind farm and other European countries are close to contesting this. Table 10.2 shows the world's 10 largest wind farms.

As can be seen in Table 10.2, London Array has the largest offshore wind farm capacity in the world of 630 MW. London Array consists of 175 Siemens wind turbines that are located 20 km off the coast. It required an investment of €2.2 billion [16]. Carbon dioxide emissions are expected to reduce by 900,000 tons thanks to the array; this is equivalent to the emissions of 300,000 passenger cars [17].

"The European Wind Energy has set a capacity target of 40 GW by 2020 and 150 GW by 2030, with the UK, Germany, Belgium and Scandinavian countries expected to provide the largest part of this capacity" [7].

Table 10.2. Ten biggest wind farms in the world [14, 15]

Capacity, MW	Wind farm	Country
630	London Array	UK
504	Greater Gabbard	UK
400	Anholt	Denmark
400	BARD Offshore 1	Germany
367	Walney	UK
325	Thorntonbank	Belgium
317	Sheringham Shoal	UK
300	Thanet	UK
270	Lincs	UK
209	Horns Rev II	Denmark

10.5 HOW IT WORKS

10.5.1 TURBINE

A basic description of the turbine design and function will be provided, as this chapter is not focused on the turbine.

The turbine either has a vertical axis or a horizontal axis.

Vertical-axis wind turbines (VAWT) have vertical main rotor shafts with the major modules, for example, the generator and gearbox, placed near the ground or at the turbine base. Their advantage is that they work with the wind blowing in any direction, having no need for orientation mechanisms. Their major disadvantage is that a significant amount of torque is required to get them to start moving.

The main rotor shaft is at the top of the turbine in the horizontal-axis wind turbine (HAWT). For it to work it has to be pointed into the wind using either a wind vane or a wind sensor with servomotor for larger turbines. Their main functions are their drawbacks as servicing and maintaining are difficult and costly. Figure 10.1 shows a HAWT and a VAWT in water, along with their basic components and respective positions.

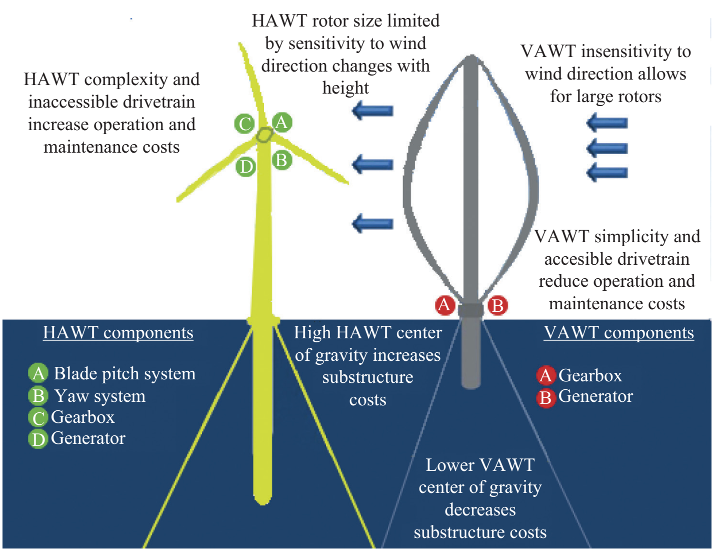

Figure 10.1. Placement of major components for HAWT and VAWT [18].

10.5.2 WIND FARMS

10.5.2.1 Shallow Water

There are different structures to support offshore wind farms depending on the depth of the water. Currently, there are several solutions for depths up to 80 m. These are summarized in Table 10.3.

10.5.2.2 Deep Water

When mounting the wind turbine is not feasible due to water depths, the only other currently available solution is to mount the turbine onto a floating structure. This concept was first tested in 2007 by Blue H Technologies, a Dutch company [20]. Being relatively new it has created avenues for research.

The placement of floating farms, far into the ocean, reduces or eliminates visual pollution (the effect of visual pollution is explored in Section 10.6). In addition, it provides fishing and shipping lanes greater accommodation. Most importantly, the absence of land and structures cause the wind to be more consistent and stronger further out into the sea [21].

Floating wind turbines are moored undersea using any of the two currently available systems—tension leg and catenary mooring. Tension leg mooring systems have vertical tethers under high tension that provide support for pitch and roll moments. There are two catenary mooring systems—buoyancy stabilized and ballast stabilized. The buoyancy-stabilized system provides low-tension lines connected to a buoyant station for the turbine. The ballasted catenary system works by employing heavy weights that hang from the midsection of each anchor

Table 10.3. Different types of structures and their associated depths [19]

Solution	Depth, m
Tripod suction caisson structures	20–80
A monopole (single column) base	30
Gravity base structures	20–80
Conventional steel jacket structures	20–80
Tripod piled structures	20–80

cable. This provides additional cable tension and thus increases the stiffness of the structure floating above the water [22].

Floating wind turbines are an instance of immature technology, as they are relatively new, they will require time and funding to improve through research. The main challenge for floating wind turbines is how transmission lines can be connected in a cost-effective method because the floating farms can be located far in the sea or ocean.

Floating offshore wind farms have more benefits over fixed offshore wind farms, which has led to research on this. Researchers are using computer models and scale models as these methods are a lot more cost-effective than having to test with an actual turbine.

There are guidelines that exist for designing offshore wind farms, such as IEC 61400-3 [23]. However, other standards are necessary in the United States and other countries that include load analysis based on site-specific external conditions such as wind, wave, and currents [24].

10.6 DISCUSSION

10.6.1 ECONOMICS

The reasons for offshore wind power are numerous. In addition to environmental benefits, there are also economical benefits for a country—it reduces energy imports, meets renewable electricity standards that many developed countries have set, and creates jobs and opportunities for the people in a trickle-over effect. One example of the benefits to the whole economy can be seen in Belfast where the harbor industry is being redeveloped to an offshore wind farm. “The work will create 150 jobs in construction of the farm, and the materials required e.g. 1 metric ton of stone from the local quarry will generate jobs in the hundreds” [25].

In addition, offshore turbines can be “located close to power-hungry populations along the coasts, eliminating the need for new overland transmission lines” [26].

Being offshore causes servicing to become a serious concern due to high costs required to reach and locate issues, and because the turbines are less accessible offshore with parts underwater. Therefore, the reliability of the offshore turbines is of utmost importance to minimize these associated costs when compared to onshore turbines [6].

In regards to maintenance, some costs include the organization that will be repairing and servicing. Majority of their costs go to the turbines alone. In order to access turbines, their modes of transport are either helicopters or service access vessels, which are both costly. In addition, depending on the distance to the shore, some of the maintenance teams will be living on-site in offshore accommodation units [27]. This adds another high cost, as an offshore structure to support these people is required. Costs for servicemen such as transport, food, water, and safety all have to be taken into consideration, which can significantly add to the cost in the long term.

That offshore wind farms are not easily accessible will generate the requirement for "remote prognosis and health-monitoring systems" [28]. These would allow planning for maintenance resulting in lower costs of operations. At the present time, "the Atkinson Center for a Sustainable Future is trying to make field data from these turbines available to all researchers as this data would allow validating complex analysis codes for designing turbines" [28]. This is a good aid in training engineers to work on wind energy.

10.6.2 ENVIRONMENTAL IMPACT

There is uncertainty as to how offshore wind farms and turbines affect marine animals and the marine environment. According to Tethys, which was developed in 2009 by the Pacific Northwest National Laboratory to support the Wind and Water Power Technologies Office of the U.S. Department of Energy, the environmental concerns of offshore wind farms and turbines include:

- Seabirds being struck by wind turbines
- Underwater noise from the installation of monopole turbines and while the turbines are running
- Marine animals' behavior being affected due to their attraction or avoidance to the turbines

One example where birds were affected by an offshore wind farm is seen with the world's largest wind farm, London Array. The first phase developed its current capacity of 630 MW, with a planned second phase to install an additional 166 turbines that would increase capacity to 1,000 MW. This second phase was cancelled in February 2014 because of the effects on a local population of red-throated divers [29]. The Royal Society for the Protection of Birds brought up the problem.

10.6.3 PUBLIC OPINION

People's views of offshore turbines vary depending on country and location. For instance, they are perceived positively in urbanized and industrial regions as some people may find them pleasant and as symbols of energy dependence and local prosperity. Some countries feel that these farms will damage tourism, whereas others feel that they will become attractions and have observation decks on top of the turbines [30].

An interesting find by Haggett is that people, who can see or have been exposed to on-land turbines from their residences, will be more inclined toward offshore wind farms [31].

10.7 CONCLUSION—IMMATURE OFFSHORE WIND TECHNOLOGIES

The main purpose for research and development of offshore wind technologies is to reduce the cost per kWh. At present, there are more economic hurdles for offshore than for onshore wind farms as costs are about 2.5 to 3 million Euros per MW, of which about 33 percent is only for the turbine. "The rest comes from infrastructure, maintenance, and oversight" [32].

In 2011, a Danish company claimed that offshore wind is not yet viable when put side by side to plants burning fossil fuels. They estimated that in around 15 years it would be, but would require significant funding for research to optimize the offshore wind farms.

Currently, there are no simulations that model external effects accurately, which causes a problem for analysis. The effects include boundary layer stability effects and wake effects. The analysis is vital for financiers so that they can predetermine the expected returns on their investment.

A panel of researchers and consultants has analyzed offshore wind farms and has suggested the following to make offshore wind farms more economically attractive [28].

- Reduce the turbine weight, which can be achieved through the use of different materials.

- Improve models for economics of wind farms and wind performance. This should cover all costs for the wind farm so that it can be optimized.
- Develop turbine load controls and strategies to minimize adverse natural effects such as damage from hurricanes.
- Eliminate faulty gearboxes as this reduces servicing costs.
- Optimize servicing methods that can include remote monitoring and diagnostics.

Research is currently underway that addresses the aforementioned to reduce costs. The Carbon Trust Offshore Wind Accelerator's goal is to reduce offshore wind costs by 10 percent by 2015 [9].

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CHAPTER 11

Industrial Sector Energy Efficiency

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11.1 INTRODUCTION

Energy is an essential part of human activity. It provides the much-needed impetus to the continuation of social beings and other living things on earth as well as enabling positive development of the economies of the world. Energy is a vital aspect in generating income in both developed and developing countries [1]. The development of the source of energy has been tremendous since the middle of the 20th century in which the bulk of the energy came from fossil fuels that were cheap in terms of monetary value and readily available to most homes and industries. As a consequence of this and due to an added human population, the energy source was exploited to a greater extent with no regard to efficient energy management. In the run up to 1960s, concerns about energy resource depletion started to take center stage in most of the international community discussions and were extended to the national level in mainly developed country jurisdictions. Despite the growing concern about resource depletion, there was no major step taken to curb the possible effect that inefficient energy use posed to the world population [2]. A decade later, the world was hit hard by the reality of resource unavailability to sustain an already energy-dependent world. During this time, two oil embargoes resulted in high cost of energy and in less than 10 years the cost of crude oil shot up by 10 times. World leaders and several energy stakeholders came together to determine the constituents that contribute to the high energy cost. There was a consensus that uneven distribution of oil and other resources, the exponential population growth, increased industrialization, and overall fuel consumption were the major factors that increased the cost of energy and led to energy resource depletion [3].

The lessons learnt from the energy crisis in this era led to a certain resolution that aimed to reduce the rate of fossil fuel consumption. To achieve the goal, steps had to be taken to increase energy management efforts and reduce consumption for a given quantity of energy output. Another step was for the energy sector to redesign the whole aspect of energy production by looking into alternative ways of energy production [4]. Energy-intensive process had to be reduced to achieve efficient energy use. However, use of alternative energy presented both cost and technological hitches since it was very expensive to develop an alternative form of energy and the technological advancement at the time did not allow for such a move [5]. Most of the technological development was still in its inception stage and thus could not sustain the demands as presented [6]. Furthermore, shutting down all energy-intensive firms to reduce energy consumption proved viable only on paper but presented a difficulty effect. Shutdown was not considered economically viable [7].

From all the proposals, efficient energy management on the side of the user proved to be a most viable and responsible approach in terms of fuel conservation and reduced environmental impact. Efficient management also proved not to stress the economic development of most countries [8]. Reduced fuel consumption impacts positively on operation cost, pollution costs, and increased competitiveness of the industry. It allows for much more independence from external energy supplies thus reducing international tensions.

Industries are the largest users of energy in the world. The United States of America alone accounts for 37 percent of total energy consumption while the other countries share the remaining 63 percent of the energy consumption. The largest consumer of energy is the transportation sector that accounts for 27 percent of the total consumption. From this concept, managing energy consumption can be made a reality from the industrial energy management viewpoint as a matter of first instance. Developing and implementing industrial energy efficiency measures has a significant potential for achieving global energy savings. Industrial efficiency measures aim to increase sustainability through various ways, such as increased recovery of waste energy and materials, improved thermodynamic efficiencies, and increased utilization of renewable resources [8]. Energy efficiency transformation presents a difficult task to the world due to the various decisional challenges that have been facing the society at all levels. However, the transformation of energy use to the positive will require society to create long-term sustainable energy systems.

Energy resources can be classified into two types. The first is the primary energy resource that consists of fossil fuels such as coal, oil, and natural gas, and thermonuclear and nuclear fuels such as uranium and thorium. The secondary energy resource forms the next class. Secondary energy is the useful forms of primary energy that have been transformed. This chapter discusses energy management best practices in the sector of industries in general. It will give specific and general examples about relevant industrial fields. The problems that face and impede the development of efficient management of energy is also discussed. The chapter also discusses goals of efficient energy management in relation to industrial development.

11.2 IMPORTANCE OF ENERGY

Energy centers on the economic, environmental, and developmental issues that the world is facing contemporarily. The general consensus of the worldview is that clean, efficient, affordable, and reliable energy cannot be dispensed with achieving the objectives of world prosperity. The modern world economies are energy dependent, and its consumption has been used to define a country's modernization and progress. Most countries that use a large volume of energy are normally considered developed. For instance, the world considers the United States as the leading country in terms of economic development. In the same line, countries that use a lot of energy in production have been faulted for the ongoing environmental effects and global warming that has hit the world in modern years. Consultative and inclusive efforts that bring together the industrialized countries and the developing countries have been encouraged to allow for international measures that can help both developed and developing countries.

In developing countries' perspective, the energy sector is needed in expanding the modern energy services with the aim of reducing poverty and improving health of their citizens. Efficient use of energy in the Third World has enabled them to improve their market competitiveness and promoting economic growth. However, despite the steps taken by both these countries, there are setbacks in attaining the efficient use of energy since the current energy systems are inadequate to meet the world's demands especially in respect to the world's poor. However, there have been reports of increasing living standards in developing countries due to small input of energy.

11.3 ENERGY EFFICIENCY

Energy efficiency can be defined as the process in which energy resources become converted into usable work. Efficiency is measured using thermal efficiency in the case of heaters, steam systems, engines, and power generators. Thermal efficiency is the ratio of the efficiency and the completeness of fuel combustion. Thus, it takes the ratio of network supplied to the combusted heat. The main purpose of an efficient energy uses borders on cost reduction that is aimed to diminish the use of feedstock energy through greater returns that allow for more production of products.

11.4 ENERGY SYSTEM PERSPECTIVE

Discussions on the perspective of the energy system are often accompanied by the defined system boundaries. The two aspects normally influence any discussion in relation to energy. The two aspects defined the right and wrong actions that should be taken and not taken by the energy stakeholders, respectively. Energy perspective can be put into various groups since almost every sector of human survival requires energy. This chapter discusses the perspective of the government and the industry since they are the big players in the energy sector.

From the position of the world authorities, energy efficiency presents different views. The first view is that energy can be viewed as a commodity. The next view borders on energy as an ecological resource, while the third and major perspective of energy views it as a social necessity. From the perspective of social necessity, consumers are said to have the right to energy supply. The fourth perspective of the energy view takes it as a factor that constitutes a strategic material or resource. As a strategic material resource, energy becomes susceptible to depletion. As a commodity, the energy becomes a necessity in the day-to-day lives of individuals and running of companies and big manufacturing industries.

The view of industrial company presents a different but related view of energy supply. However, the industrial sector does not give much attention to energy supply, energy security, and threats that energy use bring to the world in terms of increased global warming. Energy perspective in this sector borders on profitability, productivity, safety, and indoor environment. However, despite the concentration and views on energy supply, most small-sized industries have not developed measures aimed to achieve efficient energy use. To properly understand efficiency in the industry, it is important to develop an interdisciplinary approach. The interdisciplinary approach reviews the relationship among various fields, how they impact each other, and eventual energy efficiency measures. In this piece, the interdisciplinary approach will not form the basis of the study.

11.5 IMPROVING ENERGY EFFICIENCY

Improving energy efficiency takes different forms. The first form is an innovation that can lead to equal or greater output with less energy. The second form involves cutting out the energy that goes to waste. Cutting out energy that goes to waste reduces energy needed for industrial purposes while maintaining the same level of output. The third is employing heating technologies that can deliver greater output for minimal supplier energy. The creation of an innovative investment mechanism allows for accelerated technology deployment. Innovative ideas have been implemented through a network of regional cleaning energy technology centers to hasten the spread of locally appropriate energy technologies.

Managing through best practices can also improve energy efficiency if the top management of the firm incorporates the goals of the firm that relate to efficient energy use into the strategic business plan. The current business atmosphere that enhances the principle of downsizing and reduction of capital expenditure provides a good basis for efficient energy management. Senior managers concern themselves with ensuring maximization of the return on investment. The focus presents the energy managers with an opportunity to demonstrate energy efficiency as a factor that can contribute to maximization of the return on investment. Efficiency can be achieved when the energy managers gain the attention of the top management and make them understand that an efficient operation should form part of asset management in order to reduce the operating cost.

Furthermore, the firm must develop an energy management plan. The plan must incorporate energy-efficient operation as a primary component. The firm shall, therefore, run an energy-consuming device to use as much energy as necessary to fulfill the intended function. Management must ensure that the use of energy does not lead to an uncomfortable and unsafe environment. To achieve efficient energy planning, the firm must buy clean and reliable energy at the lowest cost, replacing the old equipment with the new ones and ensuring that the equipment is operated in an efficient manner.

Energy accounting is also one of the limbs of best practices in enhancing efficient energy use. The firm seeking to achieve efficient energy use must create an accounting system that it can use to locate savings and opportunities and to track and measure the success of the energy-efficient practices. In the management plan, energy accounting is a very important component. It allows the firm to keep records of its past and current state on energy use. The information enables the energy manager to communicate in a measurable way about the development of the energy management within the firm. The main purpose of energy accounting is to provide a basic foundation for strong energy administration plan, record and track progress of energy-saving strategies, and provide a platform for setting realistic energy savings. Energy accounting allows the firm to record possible areas that need improvement in the future.

The person in charge of the control of the industrial plant energy sector must ensure that he or she undertakes certain general practices that will promote energy efficiency promotion. First, he or she must ensure that regular audits are taken on the condition of the plant and regular reports made accordingly.

11.6 PRINCIPLES OF IMPLEMENTATION

Effective implementation of the energy efficiency programs requires certain candid consideration of the implementation guiding principles. These principles provide a process-like approach that industries willing to manage the use of energy should adopt in order to achieve greater efficiency. The first step is to integrate key processes to promote the implementation of identified saving opportunities. In participating in the assessment processes, the personnel must be ready for the project implementation.

The second step is to assign the completion of a specific project to specific individuals. The assigning of roles must take place after an internal approval has been conducted for each participating individual. Internal approval gives an assurance that the persons selected shall commit themselves fully to the demand of the project. The implementation requires that participating people are assigned specific duties and accorded specific roles. Understanding the project expectation is important for the participant since it allows for participation to the highest level. To achieve the required level of involvement, participants must be given handouts to act as reference documents. Energy managers, plant managers, and other staff included in the process must be conscious of each person's role and how they fit into the overall demands of the project.

The third principle demands that the implications of performing the project assessment are communicated clearly and comprehensively to the people involved. Business case for implementation must be set from the onset of the planning process. Information that can help in strengthening the business case, such as value improved energy efficiency, increased process efficiency, improved output on the environment, potential cost savings, and improved energy management, can help in developing the business case.

The company conducting the assessment must be well known to the plant managers. It is essential to establish the credibility of the company conducting the assessment. The plant managers can determine the quality of its reports, identifying assessment areas in which the organization specializes. The contract between the plant and the assessing company must define clear terms based on components of the assessment. They should create a cooperative approach toward making the assessments. The assessing company must ensure that it understands the motivational aspect that drives the company in striving to make efficient use of the energy.

The fifth principle demands that the plant must demonstrate greater commitment toward attaining the stated goal. The plant must welcome the assessment and show willingness in practice to further the project. The sixth principle involves promotion of successful identification process for opportunities. The next principle concentrates on ensuring that the identified opportunity meets the organizational rates in terms of facilities available. It points to a smooth transition from assessment to implementation. The organization can transition smoothly only when the process is accorded the needed support by the project manager and financial managers.

The eighth principle ensures that there is a continued momentum from the assessment to the implementation of the approved energy-saving projects. To achieve this, it is imperative to minimize risks that might hamper the implementation process. Financial risks must be evaluated and understood in order to avoid negative impact on energy project on production. There must be constant supplies of funding to guarantee full project implementation.

The ninth principle requires that after successful implementation, the management must quantify the energy savings benefits. The principle promotes matters of tracking the approved energy projects. It also promotes accountability by ensuring that every individual assigned a specific function is, in fact, doing so. The outcome of the project must be publicized and persons involved must be recognized. The purpose of the tenth principle is to ensure that the people involved remained motivated and committed to the sustainability of the plan and any other future project that may arise.

In this respect, the eleventh principle promotes celebrating the accomplishments with all stakeholders. Stakeholders include shareholders, boards of directors, and any other group of vested interest in the firm. It is important that the success of the projects is communicated to these classes of stakeholders, and they become aware of the energy and cost saving accomplished. The final principle denotes that the lessons learnt from the project must be taken into account in order to ensure future success. A postmortem assessment should be conducted at the end of the implementation process to ascertain aspects of the projects that have worked successfully.

11.7 BARRIERS TO ENERGY EFFICIENCY

A barrier to energy efficiency can be defined as a hypothesized mechanism that precludes the investments in technologies that are energy and economically efficient. The barriers have formed the subject of discussion and investigation since the late 1980s. It has been recognized that even the best practices that were forwarded to promote efficient energy use still fail in practical application to attain the set goals of energy conservation. Energy barriers affect the goals laid for energy efficiency programs. These barriers can be internal and external in nature and thus can be controlled when early identification and analysis are conducted to assess the importance and long-term goals of the plant.

The heterogeneity of the best practice measures in some instances fails to turn out to be cost-effective in certain cases. Heterogeneity denotes the general take of a particular technology taken to promote energy efficiency. In this respect, enforcers of the technological framework should ensure that proper assessment is conducted to ascertain that the proposed framework provides that best form of energy efficiency in theory and practice. In this respect, the principles of energy efficiency improvement must take center stage.

The next barrier to energy efficiency revolves around hidden costs. Hidden costs include the costs that relate to collecting and analyzing information. They may also include production disruptions and other inconvenience that have not been contemplated within the laid-down budget [7]. Hidden costs take a monetary value approach and thus can be avoided by proper budgeting and making miscellaneous allocations be used to cover any form of eventuality. In developing budgets, the financial department must consider the aspect of energy efficiency in the overall goals of the organization [7].

Access to capital risk also presents a monetary value perspective. Like the first two barriers, it presents impediments to energy efficiency when its availability is limited. It mainly hampers the implementation of measures aimed at making energy use and supply more efficient. For purposes of risk aversion, energy efficiency measures are constrained by short payback criteria. Most industries lack the capital that can sustain the efficiency measures since they are expensive to acquire and maintain [7]. However, long-term effects of the efficiency practices in the energy sector give the company a good profitable base.

Adverse selection presents another barrier to the energy efficiency. Ti can be classified as a type of asymmetric information. It arises when producers of energy-efficient technologies are well informed on the characteristics and the performance of the technologies on offer than the potential buyers. The information that both parties possess regarding the equipment is considered asymmetric in this respect. Asymmetric information is a form of market failure.

Principal–agent relationship also threatens efficient technologies from taking effect. The main actor that underlies principal–agent relationship is the lack of trust that shows in different levels of engagement. For instance, a company owner, who may not be well informed of the specific criteria regarding energy efficiency investments as the chief executive officer (CEO), may demand short payback rates for any such investments for lack of trust in the CEO. Such mistrust may lead to neglect of cost-effective energy efficiency investments [9].

Lack and unavailability of information may lead to the missing of cost-effective measures. As a matter of principle, all information must be communicated prior and during the course of the project to promote proper cohesion and knowledge of the facts. However, there may be a laid-down framework for passing on the relevant information to the concerned department but still achieving the goals of energy efficiency may fail. The failure may crop up from the split incentive in which certain departments fail to demonstrate proper commitment toward a common goal due to the limited gain or value the accomplishment might add to his or her department [9]. Credibility and trust accorded to the information source should be strong in order to remove any form of barriers. In a situation where the source of information regarding energy efficiency measures is not trusted and credible in the view of stakeholders, its implementation may be hampered resulting in inefficient choices being adopted.

Another factor borders on personal and human commitment to the projects aimed at ensuring that efficient measures are adopted. Where the organization lacks real ambition from within the ranks of its human resource adoption of measures to reduce the cost of energy use might prove hard [6]. Consequently, individuals who are committed to status quo of the firm may find it difficult adjusting to the new developments of energy efficiency. It can take the form of overlooking the laid-down measures or frustrating their implementation for fear of change. Human barrier cuts across both ends since it can also work to attain the heights laid down when the attitude of the employees and the top management have been positively set toward achieving efficient energy use.

The low status of the department of energy within the organization may also hamper the development of efficient measures to limit energy use. It may lead to lower priority and thus causing any proposals that they might make to the top management have a low possibility of success.

11.8 FACTORS INFLUENCING ENERGY EFFICIENCY

The intensities of energy are expressed in energy use per monetary unit. Energy intensity differs considerably in different sectors. The intensity applied to produce a similar product by different plants in different countries may differ tremendously due to a range of factors as discussed subsequently.

Access to energy resources presents contribute to differences in energy efficiency in different firms and countries. For many energy-intensive products such as steel and cement, access to quality raw materials and feedstock plays a big role in energy intensity production. Local factors such as equipment import policies, local suppliers' strategies, and limited available expertise can prevent high uptake of more energy-efficient technologies. Furthermore, capital costs have to be considered in view of energy-efficient equipment. Much of the equipment that is energy efficient costs more compared to the ones that are inefficient [5].

Plant size and age of the capital stock also contribute to the difference in energy efficiency programs. Older plants tend to be smaller, thus making them less efficient due to the old technologies that they still employ. Bigger firms that use modern technologies are more efficient [5].

However, investing on new plants and more efficient technologies do not offer a viable economic option due to the fact that the marginal production cost is smaller than it would be from the new firm.

11.9 REBOUND EFFECT

In a bid to attain energy efficiency practices, the industries stand at a risk of experiencing a rebound effect. Cost-effective energy efficiencies strengthen competitiveness by enhancing lower productions costs. The overall result of efficient energy practice is a prosperous economy for the bigger picture. In the backdrop of this popular belief, there is no certainty of positive results. The main idea is that getting the industrial companies to economize with energy can offset the expected beneficial effects [1].

The rebound might come from the behavioral response to the induction of modern technologies or measures in the production system. The rebound effect can be presented in two forms. The first is the direct rebound effect in which the new technology increases energy efficiency corresponding to a reduction in the price of energy service that would eventually lead to an increased demand for energy. The second form is the indirect rebound effect, which means that the overall energy cost is lowered by the energy efficiency technology leading to extra money left in the hands of consumers to spend on other goods and services [1].

11.10 POLICIES PROMOTING ENERGY EFFICIENCY

Governments control the use of energy through developing policies that outline energy-related targets and goals. Government policies take several forms [9]. For instance, the government might decide to increase the share on the renewable energy source within the energy sector in order to improve energy efficiency, and reduce carbon dioxide emissions from big industries. In certain instances, a government can adopt regulation that seeks to control the import of oil to its jurisdiction, improve energy reliability, and reduce air pollution [10]. Energy policies developed have been emphasized as an important factor in tackling climate change.

Governments seek to develop controlling and policy measures with the view of achieving sustainable development. From this respect, the policies and regulations developed and adopted must consider the symbiotic nature of the relationship between ecology and the economy [3]. The two aspects define each other to a great extent when it comes to sustainable development. Sustainable growth can only be achieved if the economic capacity of the country is in cohesion with the ecological demands [11]. Achieving the cohesion requires proper policy developments that can enable the achievement of the goal to be as competitive and advantageous as possible. The ecological modernization concept captures the trend whereby societies concurrently generate business competitiveness and environmental sustainability within the existing liberal market [6]. The concept involves the changing technological devices and improved innovation that the contemporary industries have undergone in the past half a century. The idea of developing regulatory policies aims to enhance green technology but to maintain the profitability of the country while befitting the environment. The ecological modernization concept serves the interest of the following groups [6]. The interest of the government is covered since it spells a low electoral risk. Industries' interests are also protected since it means incremental reform in terms of low costs of production and high output, thus high profitability, and for the society since it contain costs and creates opportunities [2].

The country is the dominant actor in the ecological modernization while industries and society play a secondary role. As the regulator of the market, the government plays the role of an "enabler" of the development of the green market [3]. As an enabler, the government oversees the enforcement of policies and regulations and sets standards that should be met by the industries through the national energy department. However, in developing policies, the industrial companies must participate in the policy development processes [2].

11.11 CONCLUSION

This chapter has dealt with various areas that threaten the efficiency and those that promote energy efficiency. Energy stakeholders must ensure that policies and regulations that the government provides are aligned with the industry goals in view of energy efficient use. Energy efficiency must be attained in a sustainable manner in which proper consultative engagement is enhanced to promote greater involvement. Due to the globalization brought by technological development, efforts to conserve energy must go beyond the boundaries of the particular countries. They must involve the international community through international forums in which effective way to promote efficiency are discussed in an elaborate way. Engineering practices should be developed to meet the current demand of energy needs of the industries and the needs of the population at large with a view of creating new and efficient practices. The main focus should be put in the area of innovation that can assure of the manufacturing of good and reliable machines that can effectively achieve proper energy management. Managing energy efficiently requires that a positive attitude is developed within the ranks of energy stakeholders. It is important that every industry and every individual understand that energy management standards are aimed to provide guidance and not to defeat the economic advancement of the industrial institutions. Every facility must ensure that it develops an energy management plan within its business plan in order to allow for future consideration and improvement since it forms part of the greater business project.

In firms in which energy plans have not been laid into the business plan, commitment to the energy regulations, policies, and efficiency measures is normally viewed in contempt and thus presents a barrier to energy efficiency. The management standards should be coherent in nature and give the true reflection of the industrial plant in terms of financial commitment and goodwill. Accountability measures should also be adopted to promote transparency in the energy management sector within the firm. Accountability enables external stakeholders like the government to access operations of the company and thus puts it in a good position to make a clear and believable report on the energy sector within the country. The government and the energy industries should develop structures that allow for capacity building. A careful, organized training program can attain significant goals in according engineers the needed knowledge and skill in energy optimization techniques. Procedures for selection of engineers for the specific trainings should be properly laid down in a transparent manner to avoid any corrupt practices. Experts for these training may come from government-sponsored energy centers, factories and consulting companies, and equipment-manufacturing engineering companies.

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CHAPTER 12

Commercial Sector Energy Efficiency

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12.1 INTRODUCTION

The U.S. Energy Information Administration (EIA) collects, analyzes, and disseminates independent and impartial energy information to promote sound policy making, efficient markets, and public understanding of energy and its interaction with the economy and the environment [1]. A number of papers and studies referenced in this chapter rely on the most recently completed Commercial Buildings Energy Consumption Survey (CBECS), published in 2003. It is therefore necessary to note that some of the data, and thereby the conclusions drawn from that data, may not accurately represent the most current trends in energy efficient technology and their adoption. However, the conclusions drawn and insight into the technology adoption process are applicable to current trends in innovation.

12.2 TRENDS IN COMMERCIAL SECTOR ENERGY CONSUMPTION IN RECENT DECADES

According to the EIA, 10,785 trillion British thermal unit (Btu) out of a total 57,906 trillion Btu is used by the commercial sector in the United States. This accounts for roughly 18.6 percent of the nation's energy use [1]. This figure has not changed significantly in the past decade. In 2004, the percentage of energy consumed by the commercial sector in the

United States was also 18 percent [2]. On a global scale, the International Energy Agency (IEA) has shown that between 1984 and 2004, primary energy has grown 49 percent and CO_2 emissions have grown by 43 percent, with an average annual increase of 2 and 1.8 percent, respectively [2]. According to the IEA, "[Primary] energy commodities are either extracted or captured directly from natural resources (and are termed primary) such as crude oil, hard coal, natural gas, or are produced from primary commodities [3]." Pérez-Lombard, Ortiz, and Pout [2] show that primary energy consumption (between 1973 and 2004) has grown at a more rapid rate than the population, thus displaying a rate of increase in the per capita value. Pérez-Lombard also mentions that one trend is the rise in share of energy consumption from heating, ventilation, and air conditioning (HVAC). The demand for thermal comfort has dragged HVAC use to account for nearly 50 percent of the total end use of energy in commercial buildings in the United States. In Figure 12.1, the EIA's consumption by end-use table for commercial buildings (based on CBECS 2003 data) is shown.

There are, however, trends in energy use and efficiency that have positive implications. A study published for Bloomberg Finance in 2013 showed that, since 1980, energy intensity in commercial buildings has decreased more than 40 percent. Energy intensity is defined by the EIA as the ratio of energy consumption to a measure of the demand for services. In this chapter, the demand measure will be the floor space of a building. This decrease in energy intensity can be partially attributed

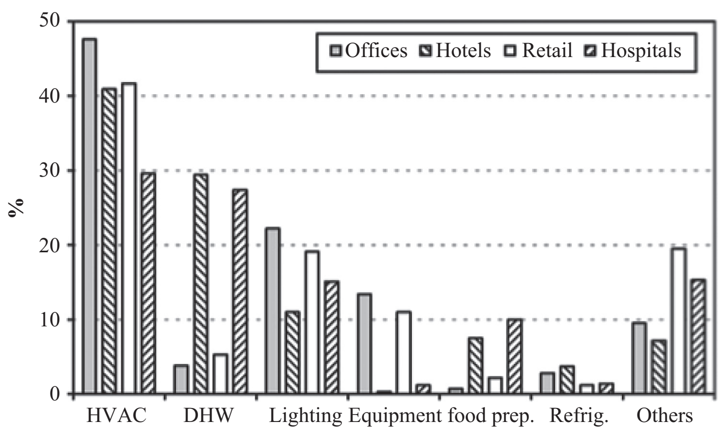

Figure 12.1. Consumption by end use for different building types. DHW, domestic hot water.
Source: Reproduced from EIA [1].

to higher levels of efficiency in new buildings and improvements made in the energy efficiency of older buildings. The study also shows that, while there are far more electricity-consuming appliances in a commercial building in 2012 than in 1980, buildings today are not consuming significantly more electricity per square foot than they were in 1980. The obvious conclusion is that increased electricity use and plug loads have been offset by improvements to HVAC and lighting, as well as other efficient improvements [4].

According to Andrews and Krogmann [5], between 1950 and 2006, the growth in energy use allocated to the commercial end-use sector averaged 2.8 percent annually, most of it in buildings, reflecting both a growth in the sector and a shift toward electricity (which has large associated system energy losses). Comparatively, the overall U.S. energy consumption increased by an average annual rate of only 1.9 percent [6]. The comparable rate for the residential sector was only 2.3 percent during the same interval and was 3.4 percent for real growth in gross domestic product [7]. As mentioned before, the reality that commercial buildings account for 18 percent of primary energy use necessitates innovations to reduce commercial building energy use and carbon footprint.

Andrews and Krogmann [5] further illustrate the trends in commercial sector growth in recent decades. A 2003 snapshot of the commercial sector [8] shows the following. About 63 percent of the commercial floor space that currently exists in the United States was built after 1970. Additionally, a majority of commercial buildings are home to a single establishment. The median building floor space is 5,000 $ft.^2$ while the mean of the right-skewed distribution is 14,700 $ft.^2$ A geographical distribution shows that the Northeastern United States is home to 20 percent of the commercial floor space, while the Midwest has 25 percent, the South has 37 percent, and the West has 18 percent. Figure 12.2 shows the total commercial floor space and energy intensity (in kWh of energy entering the site per square meter of floor space) by year built, according to the 2003 CBECS survey [5].

The initial need for technologies designed to improve energy efficiency was felt due to the oil price shocks of the 1970s and the regulatory initiatives that followed. Some of the most noteworthy and impactful innovations have been new types of mechanical systems, lighting options, and building envelopes (passive elements such as windows, roofs, and insulation). These innovations have come in parallel with the practice of cooling commercial buildings for comfort. Plug loads have also increased for computers and other electronic equipment [5].

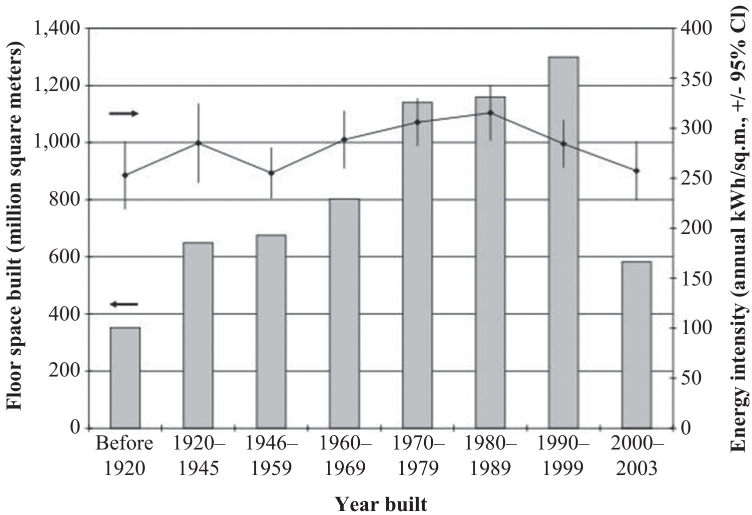

Figure 12.2. Energy intensity and floor space of U.S. commercial buildings by year built.

12.3 TRENDS IN INNOVATIONS IN ENERGY EFFICIENT TECHNOLOGY FOR COMMERCIAL SECTOR USE

The EIA publishes an *Annual Energy Outlook* (AEO), in which statistical trends in data are used to yield potential predictions on energy use. The 2014 AEO provides energy-use data for the commercial sector from 2012 and predicts what the same data might look like in 2040. It is predicted that the trend of decreasing commercial sector energy intensity will continue for most electric end uses in a reference case, while commercial floor space will increase by 1.0 percent annually. In 2012, electricity accounted for 54.5 percent of commercially delivered energy use in 2012 [1].

Note that energy intensity is measured at site boundary and does not account for losses of primary energy associated with electricity production [5].

The EIA's predictions beg a number of questions. First, what are the innovations that can enable the continuation of the trend of the decrease in energy intensity? Second, which of these innovations are being adopted by the commercial sector? Third, why do certain innovations succeed while others are not taken advantage of despite the possible benefits?

In the study conducted by Andrews and Krogmann [5], there are a number of innovations described. Some of them may no longer be cutting edge (as of 2014) but serve to provide an insight into the historical patterns of technology diffusion and the performance outcomes resulting from these innovations. Sadineni, Madala, and Boehm [9] provide a more recent (2011) exhaustive review that covers building envelope components and passive energy savings. Envelope components are those that constitute the passive portions of the building and include walls, windows, roofs, thermal insulation, thermal mass and phase change materials, and infiltration and airtightness [9].

One area of innovation is window treatments. The options for windows include single-layer glass, multilayer glass, a combination of both, tinted window glass, reflective window glass, external overhangs or awnings, and skylights or atriums. Multilayer glass is an innovation where two or three pieces of glass are separated by air space to improve insulation against heat transfer. Reflective and tinted coatings are features installed on the exterior glazing of the building to reduce the rate of solar penetration of the building, thus reducing the need for cooling. External overhangs and awnings provide shade from outside to the same end as the window coatings. Skylights or atriums that are designed for lighting purposes can reduce lighting needs by allowing daylight access [5]. Windows are also subject to a number of glazing materials and technologies. They include aerogel glazing, vacuum glazing, switchable reflective glazing, suspended particle device films, and holographic optical elements [9].

The walls of a building are a passive element that also has an effect on the efficiency of a building. Passive solar walls, lightweight concrete walls, ventilated or double skin walls, and walls with latent heat storage are all options for improving energy efficiency. The roof of a building is of similar importance. Types of roofs include masonry roofs, lightweight roofs, ventilated and microventilated roofs, vaulted and domed roofs, solar-reflective and cool roofs, green roofs, photovoltaic (PV) roofs, and thermal roof insulation systems [9].

Lighting types include incandescent, standard fluorescent, compact fluorescent, high-intensity discharge (HID), halogen, and others. Incandescent bulbs have been phased out under federal legislation as per the Energy Independence and Security Act of 1007, P.L. 110–140, H.R. 6, which essentially raised the efficiency requirement for incandescent bulbs beyond their capabilities. This was due to the significant amount of energy lost as heat by incandescent lighting. Fluorescent lamps are typically long, narrow tubes with a fluorescent material coating on the inside. They produce light by passing electricity through mercury vapor, causing the fluorescent material to glow. Fluorescent lighting is now being produced widely in standard light socket sizes to fill the void left by incandescent bulbs. HID lamps produce light by passing electricity through a gas, which causes the gas itself to glow. They have extremely long lives and emit more lumens per fixture than fluorescent lights. Another lighting type is a halogen lamp, which is a type of incandescent light that is longer lasting and more efficient than standard incandescent bulbs. It employs halogen gas, usually iodine or bromine, which causes the evaporating tungsten to be redeposited on the filament. They are also capable of burning brighter and whiter than standard incandescent lights [5].

Some conservation features surrounding lighting are daylighting, daylighting sensors, specular reflectors, electronic ballasts, and control systems for daylighting. Daylighting is an architectural strategy where the percent of an occupied floor area that relies on natural daylight alone is maximized. Daylighting sensors are applied in tandem with daylighting architecture to reduce the amount of electric lighting used by varying the output of the system based on available daylight. A specular reflector is a mirror-like backing feature on fluorescent light fixtures designed to reflect light into the room, thereby increasing the amount of light provided by each fixture and reducing the number of lights needed. Electronic ballast is a lighting conservation feature consisting of an electronic version of conventional electromagnetic ballast. The ballast is the transformer for fluorescent and HID lamps and it provides the necessary current, voltage, and waveform conditions to operate the lamp. Other control systems use microprocessors and sensors to manage timing and intensity of lighting according to predefined rules [5].

Heating equipment types include furnaces, boilers, packaged heating units, individual space heaters, heat pumps, district steam or hot water, and other heating equipment. Furnaces burn fuel or use electrical resistance to heat air directly without steam or hot water. The hot air is then distributed throughout the building, typically by air ducts. Boilers burn various fuel types to heat water or steam and can either be held within a building or in a central plant. Andrews and Krogmann consider those held within a central plant to be district heating. Packaged heating units are factory assembled and installed as units, as opposed to being custom assembled for the building. They are generally mounted on the roof of the building and produce warm air for distribution through ducts. Space heaters are free standing and utilize no ducts or piping. Heat pumps draw heat into a building from the outside and, during the cooling season, eject heat from the building to the outside. They are essentially vapor-compression refrigeration systems whose indoor–outdoor coils are used reversibly as condensers or vaporizers, depending on the need for heating or cooling [5].

Cooling equipment includes residential-type air conditioners, heat pumps, individual air conditioners, district chilled water, central chillers, packaged air-conditioning units, swamp coolers, and others. Central chillers produced chilled water in order to cool air, which is then distributed throughout the building. They are generally installed outside the building. The other types mentioned are similar to their heating equivalents. Available HVAC conservation features tracked in CBECS include variable air volume (VAV) systems, economizer cycles, HVAC maintenance, and control systems. VAV systems vary the quantities of conditioned (heated or cooled) air to different parts of the building according to the heating and cooling needs of those specific areas. An economizer cycle is an HVAC conservation feature consisting of indoor and outdoor temperature and humidity sensors, dampers, motors, and motor controls to reduce the air-conditioning load. The system varies based on how much outside air is brought in depending on the favorability of the temperature and humidity conditions. Maintenance is also a crucial conservation method to ensure that HVAC systems are operating properly [5].

Andrews and Krogmann [5] compare data taken from CBECS 1992 to 2003 regarding which buildings utilize different types of essential measures and which buildings employ advanced and energy efficient variations in the basic technologies. The first question they answer is: What are the trajectories of technology adoption within U.S. commercial buildings? They show that window treatments in the United States have changed in several ways over time. The usage of single-layer glass has dropped and double-layer, tinted, or reflective glass capable of reducing heating and cooling loads are used across the board. The reliance on awnings and overhangs has remained fairly constant [5].

Lighting technologies are shifting away from the use of incandescent bulbs. Traditional fluorescent tubes are also being replaced by energy efficient compact fluorescents as well as higher-performance HID lamps and halogen lamps. Lighting conservation features associated with the installation of fluorescent lighting have increased significantly. Specular reflectors have gone from 22 percent usage to 36 percent and electronic ballasts have risen from 5 to 65 percent of usage on commercial floor space. Lighting sensors and control systems have been slow to advance and the reliance on daylighting has not changed significantly, remaining at about 14 percent [5].

Space heating fundamentals have progressed slowly and the adoption of packaged products has risen in both new and old buildings. District heating and custom-assembled boilers are declining while packaged units and heat pumps are rising in use [5].

Space cooling, as a widespread concept in commercial space, is a relatively recent advancement. Central chiller systems, which rose to popularity in the 1970s, still play a significant role. District chilled water systems are mainly used on campuses and packaged systems are especially popular, having been installed in nearly half of new buildings. Heat pumps and other packaged technology have also risen in use. HVAC conservation systems are being widely implemented. VAV systems, economizer cycles, and energy management control systems are being installed in nearly half of the new buildings. Regular HVAC maintenance is now a standard practice in a vast majority of commercial buildings [5].

12.4 DO THESE ENERGY EFFICIENT INNOVATIONS LEAD TO TRUE ENERGY SAVINGS?

Overall, the results of Andrews and Krogmann indicate that new technologies are slowly displacing old ones with substantially varying rates and levels of penetration. The second, follow-up question is: Do these technologies influence the energy intensity of commercial buildings? In 1997, the EIA claimed that energy conservation measures were widespread, referring to many of the aforementioned technologies. Many of these technologies are identified as energy conservation measures in local statutes and are recommended by energy efficiency experts. Engineering analyses also predict that these measured can save energy due to their increased efficiency. However, in the CBECS 2003 data set, buildings that employ innovative HVAC technologies, window treatments, and lighting technologies are likely to be more, rather than less energy intensive. They are also likely to be more electricity intensive [5].

The answer, according to Andrews and Krogmann, as to whether the innovative technologies reduce the energy intensity of commercial buildings was not so clear in either direction, but leaned toward “no.” Energy intensity in U.S. commercial buildings was shown to be strongly a function of the price of energy, the required operating schedule, and the amount of exterior glass. Scale economics also play a role, meaning that larger buildings are often less energy intensive, in part due to a lower surface area-to-volume ratio, and in part due to improved technological opportunities. Andrews and Krogmann’s results show that, with the exception of daylighting, the so-called innovative HVAC, window, and lighting efficient technologies are associated with higher rather than lower energy intensities [5].

There are, however, other studies that yield more positive results. Kneifel [10] attempts to determine the energy savings and cost-effectiveness of certain energy efficiency improvements, the resulting carbon emission reduction, and the impact a government-imposed cost on carbon emissions could have on energy efficiency investment decisions. He uses life cycle costing (LCC) and life cycle assessment with "extensive building cost databases," whole building energy simulations, state-level emission rates, and statewide average utility rates to arrive at his conclusions. His study consists of testing 12 building types, which are shown to constitute 46 percent of the U.S. commercial building stock floor space. LCC and life cycle assessment are conducted over four different study period lengths:1, 10, 25, and 40 years. The one-year time period, unlike the others, represents an investor who intends to turn over the property soon after completion [10].

Each of the 16 building types is simulated in each of the 16 U.S. cities located in different ASHRAE 90.1-2004 subclimate zones. The analysis then designs each building according to three separate standards: the ASHRAE 90.1-2004 (considered to be the base case or control), the ASHRAE 90.1-2007, and a higher efficiency "Low Energy Case" (LEC) design. Insulation and windows, specifically, are the components changed to meet the ASHRAE 90.1-2004 and ASHRAE 90.1-2007 standards. The LEC design standards further increase the thermal efficiency of windows and insulation while introducing daylighting and window overhangs. Daylighting controls and overhangs are based on the *EnergyPlus* "Example File Generator" recommendations. Each of the three efficiency designs also alters the size of the HVAC systems required due to the altered heating and cooling loads of the building. Consequently, the lower cost of the smaller HVAC system can offset some, if not all, of the additional energy efficient investments. In the study, proper maintenance costs as well as energy and labor costs are included [10].

The results showed the LCC, carbon emissions, and carbon cost savings of each test case. LCC was analyzed via two measures: net savings as a percentage of the base case LCC and the adjusted internal rate of return (AIRR). AIRR can be seen as the annualized return on the initial energy efficiency investment costs. For a one-year study period, the ASHRAE 90.1-2007 did not lead to energy use reductions in every case, and did not reduce the energy use very much in any case. The LEC design, however, led to energy use savings of 3.2 to 44.2 percent relative to the control case. Colder cities were shown to have the smallest savings in energy costs while cities in more temperate climates have the greatest savings. The LCC results were greatly influenced by the study period, as was expected. The LEC design was the most cost-effective choice for only 50 percent of the 192 building types over a one-year study period. This indicates that in 50 percent of cases, the investment in higher efficiency building practices, when applied in an integrated design context, can pay for itself within one year. When the study period length was increased to 10 years, the LEC was the most cost-effective for 69 percent of building types. When increased to 25 years, LEC was the most cost-effective for 88 percent and when increased to a 40-year study period LEC was the most cost-effective for 93 percent of building types. The AIRR increased with the study period length as well. For all study periods, the AIRR was above 10 percent in 56 percent of building types. Negative AIRRs were calculated at 41 percent for a 1-year study period, 20 percent at 10 years, 8 percent at 25 years, and 4 percent at 40 years. Obviously, the initial costs were constant and, over time, the energy efficiency benefits became increasingly cost-efficient [10].

Life cycle carbon dioxide equivalent emissions changed significantly with the implementation of LEC standards. Over a 10-year study period, the change in emissions ranged from a 0.5 percent increase to a 32.6 percent decrease. However, the life cycle CO_2 equivalent reductions are lower, percentagewise, than operational energy CO_2 equivalent reductions since more material is required to manufacture some of the energy efficiency improvements. In every location where the LCCs were reduced, the cost of reducing carbon emissions is negative, accounting for 80 percent of buildings over a 10-year period. The mean cost per ton of CO_2e drops from over $1,000 for a one-year study period to -$108 for a 10-year study period. The apparent difference over 10 years can be used to highlight the significance of LCC in pushing the financial case for carbon-reducing technologies and their integration in building design [10].

Kneifel's conclusions indicate that energy efficient measures cannot be evaluated without considering the LCCs, a task not undertaken by Andrews and Krogmann. The simulated results are quite positive and encourage the implementation of energy efficient systems. They even suggest that, because of the decrease in the cost of CO_2e, the government could take actions to further encourage the adoption of these technologies. The effect would be a greater disparity in the LCCs of buildings with and without energy efficient measures [10].

Another study intended to evaluate the real results of energy efficiency measures is the evaluation of Leadership in Energy and Environmental Design (LEED) results conducted by Cropp, Lee, and Castor [11]. LEED certification program for new commercial construction lacks a mechanism to verify proposed energy savings. There are some inconsistencies in the findings on LEED-certified buildings. The Energy Trust of Oregon's team evaluated 36 LEED buildings in Oregon receiving Energy Trust incentives between 2008 and 2011. The paper reviews evaluation findings for program realization rates, savings relative to baseline consumption and energy use intensity (EUI), compared with the 2003 CBECS and an Oregon commercial new construction study [11].

LEED's goal with EAc1 credits is to rate buildings based on energy savings relative to new and existing commercial construction projects not pursuing a green building rating. However, whether LEED-certified buildings actually save energy is in question. LEED's rating system awards energy-savings points for the design intent as reflected in a building's simulation model and for exceptional savings calculations. They do not, however, have a mechanism that allows the U.S. Green Building Council to verify that the proposed measures and simulation results have been installed and operating effectively. There are a number of ways the simulation results can be undermined between concept and implementation. Building owners or developers may deem energy efficiency measures to be not cost-effective or valuable and exclude them from the final building design. The facility management staff may not effectively commission mechanical systems despite LEED providing points for building commissioning. In addition, the building's operators may choose to override certain energy efficient HVAC controls to address tenants' complaints regarding comfort issues [11].

Results include a realization rate, which is the ratio of evaluated-to-reported energy savings. Based on the building's gross square footage (gsf), annual electricity consumption, and annual gross gas consumption, the building's EUI was calculated. On average, the projects achieved average gsf-weighted savings of 23 percent over the baseline building's energy consumption. They also had a gsf-weighted realization of 90 percent. Another indication of the results is that, in regard to the LEED process, the number of EAc1 points represents a better comparison for energy savings achieved than the LEED rating. The study also examined the relationship between site and source EIU to determine whether LEED buildings also saved source energy. With the exception of college and university buildings, the evaluated LEED buildings achieved lower source EUIs than the reference study buildings [11].

The results cannot be used to represent the population of LEED-certified buildings because the sample is so small and in one geographic area. The results, however, did show a correlation between LEED EAc1 points and evaluated energy savings. There is also a correlation between the number of LEED EAc1 points and the percent energy savings over baseline consumption. However, these correlations are likely strengthened by the Energy Trust's incentives that help ensure proper implementation of energy efficient procedures. In other words, measures that might otherwise have been deemed to be not cost-effective are still implemented with the help of these incentives. The scrutiny of the implementer also encourages simulation modelers to use more realistic assumptions. The program's commissioning measure also provides further incentive to optimize performance of mechanical systems and controls, which can then better reflect the intended benefits of a LEED-certified building [11].

Andrews and Krogmann [5], Kneifel [10], and Cropp, Lee, and Castor [11] provide an answer to the question of whether energy efficient technologies and measures serve to reduce energy consumption and costs, as they are expected to do. The overall conclusions are quite positive and even provide constructive criticism as to where the evaluation and implementation of commercial buildings' energy efficiency can be improved.

12.5 ADOPTION OF ENERGY-EFFICIENT INNOVATIONS IN THE COMMERCIAL SECTOR

Thus far, a number of available innovations have been reviewed. Their effectiveness has been reviewed as well. However, in order to better understand commercial sector energy efficiency, it is necessary to ask an additional question. Why do certain technologies integrate into the market slowly while others integrate more quickly? It is important to understand the concepts of innovation systems or a modification thereof [12] as they pertain to technological change.

Shama [13] provides certain insights as to how and why energy efficient measures get adopted. He claims that the low percentage of adoption of newer, energy efficient technologies cannot be understood solely from the viewpoint of the engineer or the economist. The engineering efficiency improvements essentially dictate accomplishing the same output with a lower input energy. In economics, the goal is to accomplish the same output task while spending the least on inputs, whether energy costs or labor costs. Engineering and economics together are capable of presenting numerous seemingly beneficial solutions; yet sometimes they are not adopted. It is necessary to incorporate a behavioral perspective to fully understand this phenomenon [13].

The behavioral perspective of conserving energy is based on two main concepts. "The first is that some changes in consumer behavior are, in themselves, important sources of conservation energy. The second is that conservation energy is an innovation whose use is determined by behavioral effects [13]." In other words, the users of the technology have to choose whether to use their technology in an efficient manner or not. Examples include turning off lights on leaving a room or being conscious of the thermostat temperature. The potential to conserve energy presented by engineering and economic concepts cannot be fully realized unless the consumer chooses to adopt it. However, at the time, and still today, U.S. energy policy makers were reluctant to emphasize such behavioral potentials for energy savings. They do not want to be accused of advocating drastic lifestyle changes and thereby discourage the public from embracing innovations [13].

One somewhat measurable product of the behavioral factor is known as the rebound effect. Qiu [14] discusses the rebound effect as an econometric analysis of energy demand in the commercial building sector. The rebound effect is the phenomenon wherein the adoption of energy saving innovations may induce an increase in the usage of the corresponding technologies and thus can possibly increase energy consumption [14].

Qiu conducted his study based on the EIA's definition of a commercial building and analyzed the actual energy savings of several correlated technologies in commercial buildings in the United States. The results of his model, which adopted at least one of the three specified HVAC and five specified lighting efficient technologies on average for commercial buildings, showed that electricity consumption was reduced by 35 percent. He also estimated that the own price elasticity, the quantity demanded divided by the percentage change in price, of electricity consumption and natural gas consumption are −0.56 and −0.4 percent, respectively [14]. Thus, the rebound effect can be rejected as an argument against the adoption of energy efficient innovations in commercial buildings.

The implications of Qiu's [14] findings are that pricing or tax policies aiming to reduce energy consumption by increasing the costs of consuming energy in commercial buildings will be more effective in reducing the electricity consumption than the gas consumption. The specific tax, however, must be carefully placed so as not to impose welfare distortions [14].

The second concept of diffusion of innovations helps to explain why there is such a low adoption rate of energy conservation innovations. Even if a product has the numbers to prove efficiency and cost-effectiveness, it is not necessarily quickly integrated. With energy efficiency innovations, the advantages may not seem immediately obvious. There are many factors to take into account and one single innovation is mixed with the numerous other systems and uses in a given building. What is obviously cost-effective in one scenario may not be obvious in another. The advantages must be presented to the customer as relative to their existing services [13].

There is also an element of risk involved in the adoption of innovations. If a consumer has a product, or a method of obtaining energy services, he or she may perceive a risk in switching away from that method. Another risk is that of not receiving a return on the initial investment. If an owner plans to move or sell, he or she may not believe that his or her return will occur quickly enough [13].

The issue of compatibility is that a specific innovation needs to be applied in numerous environments and situations. The social values of the product must also be compatible with the consumer. Diffusion research also typically assumes that, with an innovation, the other surrounding variables remain constant. For example, except for the innovation itself, one can safely assume that little change was associated with the introduction of aluminum foil, saran wrap, or even microwave ovens. In such cases, the degree of compatibility or "fit" of these innovations is measured against constant values. However, this is not the case with energy conservation innovations. The social values of a society are, in some way, related to the need for more energy efficient technologies. Consumption patterns and quality of life change fairly rapidly in today's world. It is therefore important for energy policy makers to emphasize that energy efficient innovations provide the same, if not greater, level of comfort [13].

The adoption process goes through numerous stages: awareness stage, interest stage, evaluation stage, trial stage, and finally adoption stage. A trial stage is a difficult stage to achieve for many innovations as they are often permanent installments. It is sometimes impossible to temporarily install a full system for a trial run. Also, the full scope of the potential uses and advantages must be made apparent to the consumer [13].

Hekkert *et al.* [12] propose a new approach for analyzing technological change called "functions of innovation systems." It is argued that the concept of innovation systems suffers from two major flaws. First, it is too static. Second, it lacks sufficient attention for the microlevel. The framework proposed focuses on the most important processes that need to take place in innovation systems to lead successfully to technology development and diffusion. By mapping those processes over time, Hekkert *et al.* create insight into the dynamics of innovation. The scope of their framework will not be discussed here. It is important to mention, however, as it pertains to the understanding of diffusion of energy efficient technology. Innovators and consumers alike should study these processes so as to understand how and why an innovation can be beneficial.

12.6 A FOCUS ON THE EXAMPLE OF SEMITRANSPARENT PV WINDOW TREATMENTS

Miyazaki, Akisawa, and Kashiwagi [15] conducted a study based on semitransparent solar cells used in the windows of buildings. The purpose of the study was to determine the optimum solar cell transmittance and window-to-wall ratio (WWR), and to estimate energy savings of the building. This is a fairly new concept as far as implementation is concerned, and very few buildings have installed such technology. Their study was based on a computer model where a standard floor of an office building was simulated. An annual energy simulation was performed with *EnergyPlus*.

The results showed that a solar cell transmittance of 40 percent and a WWR of 50 percent achieved the minimum electricity consumption in the building when the artificial lighting was controlled with daylighting. By using the optimum PV window, the electricity consumption was reduced by 55 percent compared to the single glazed window with a WWR of 30 percent of lighting control [15]. In their conclusions, they note that the study did not consider the influence of shading by the surrounding buildings, which would reduce the benefit of daylighting and the PV output. They assumed a constant coefficient of performance in their measure of total electricity consumed and they note that their future work should incorporate HVAC systems. They also measured the improved performance against a single glazed window, a practice that, as noted by Andrews and Krogmann [5], is no longer relevant.

Miyazaki, Akisawa, and Kashiwagi also note that in precedent studies it has been shown that a large window size results in the increase of a cooling load but a reduction in heating load because of increased solar heating gains. Daylight is a crucial factor to account for, not only because of its effects on heating and cooling loads, but because of its potential effects on energy used for artificial lighting. Because windows play such a crucial role already, it can be practical to add the functionality of PVs [15]. The specific technology is still being developed and optimized and will be discussed later.

Fung and Yang [16] also conducted a similar study. They constructed a one-dimensional transient heat transfer model for evaluating the heat gain of semitransparent PV modules for building-integrated applications. The energy transmitted, absorbed, and reflected in each element of the building-integrated PV modules, such as solar cells and glass layers, was determined. It was found that more than 60 percent of the total heat gain through the modules came from radiated solar heat gain (as opposed to conduction from outside air). The values ranged between 8 and 29 kWh/m^2 per month throughout the year for modules facing different orientations. They were also able to establish that the area of a solar cell in a given PV module has a significant effect on the heat gain. Nearly 70 percent of the heat gain could be reduced if the solar cell area ratio is 0.8 [16].

Li *et al.* [17] confirm the potential benefits of solar energy conversion via the use of semitransparent PVs in office buildings. They tested a PV module in Japan and conducted their study based on a building in Hong Kong. Their results, however, are applicable in most cities with small adjustments. They constructed four cases each with a different combination of two variables as follows. Case 1: no dimming controls and no semitransparent PV modules replacing tinted glass for southwest (SW)-facing windows. Case 2: dimming controls but no PV modules. Case 3: no dimming controls but PV modules installed in SW-facing windows. Case 4: dimming controls and PV modules installed. Note that the decision to only install PV modules on the SW-facing walls was due to the high cost of the PV units and the low sun exposure of the northeast orientations. A number of other energy efficient technologies were included in the simulation such as dimmable electronic ballasts and four separate lighting zones. The full details of the reference building will not be discussed here. Table 12.1 shows the electricity benefits of cases 2, 3, and 4 relative to the reference case (1) for a one-year study period [17].

The financial benefits are dependent on the cost of energy and the results obviously change with various buildings. The environmental benefits in terms of CO_2 emissions were also determined to be significant [17].

Table 12.1. Electricity benefits (electricity generated and electricity saved) for cases 2, 3, and 4 [17]

	Electricity benefits (MWh)
Case 2	1,175
Case 3	200
Case 4	1,200

One particular innovation, solar panels printed using ink-jet printers onto a conductive polymer, is an interesting case in which a product that is seemingly highly useful was not adopted by the commercial sector, or any sector for that matter. This is not to say that it will never find its way into the market. It makes for a good example of some of the adoption principles discussed earlier.[1]

The technology, branded under the company Konarka Technologies (filed for bankruptcy in 2012), was a unique innovation. Unlike current solar cells, based on silicon, it utilized a light-sensitive dye in which PV elements were dissolved. The dye was then printed onto a conductive polymer, invented by cofounder and Nobel Prize winner Alan Heeger. The potential advantages of the thin-film solar panels are numerous. The production is inexpensive, utilizing a factory that was previously used for common ink photo printing. It is capable of being mass printed at very high rates. Table 12.2 shows the energy required for manufacturing, carbon footprint, and energy payback in years as calculated by Konarka. Additionally, it is lightweight and flexible, making it less expensive to install and capable of being transported less carefully than rigid solar panels. Because of how it is printed and the nature of the circuit, one could, in theory, pound a nail through it with virtually no harmful effects to its productivity.[1]

One of the main drawbacks is that air and water are capable of degrading them. A solution to this problem is to use them in applications similar to the PV windows discussed previously. If they are installed

Table 12.2. Benefits of Konarka's "plastic" solar panels as related to other types of solar panels (A. Heeger, Nobel Laureate and co-founder Konarka Technologies, personal communication, November 24, 2014)

Technology	Energy for production ($MJ.Wp^{-1}$)	CO_2 footprint ($gr.CO_2$-$eq.Wp^{-1}$)	Energy payback time (years)
mc-Si	24.9	1,293	1.95
CdTe	9.5	542	0.75
CIS	34.6	2,231	2.71
Flex OPV	2.4	132	0.91

CIS, copper–indium–selenide; OPV, organic photovoltaic.

[1] A. Heeger, Nobel Laureate and co-founder Konarka Technologies, personal communication, November 24, 2014.

between the two panes of a double-paned window they can remain protected from the elements and last longer. Another major challenge and reason for initial failure was the efficiency, which, at the time of initial production was in the low single digits.[1]

The research has not stopped due to the failure of the company. Current efficiencies achieved in the laboratory are between 11 and 12 percent and about 10 percent in production while silicon solar cells achieve 18 to 20 percent. This disparity will need to be overcome for the product to be viewed as competitive and advantageous. There is currently a building in Florida, which houses the Arch Aluminum and Glass Company, which has Konarka's solar cells installed. Mr. Heeger remains excited and hopeful about the product's usefulness and potential for later integration.[1]

12.7 DISCUSSION AND CONCLUSIONS

In this chapter, current and recent trends in commercial sector energy efficiency were reviewed. A number of innovations claiming to be beneficial to commercial buildings and their energy efficiency were reviewed. Their penetration into the current market was also discussed. The significant conclusions were that, despite the rebound effect and the slow rate of diffusion, energy efficient technologies are capable of reducing the amount of energy consumed by a commercial building significantly. The trend of energy intensity in commercial buildings was shown to have been decreasing since 1990, a step in the right direction. As the commercial sector continues to grow and the demand for thermal comfort and devices that consume energy grows, innovative technology must be introduced so that this trend can continue.

In an LCC and carbon emission analysis of commercial buildings it was found that when buildings adopted a specified arrangement of energy efficient technologies, a vast majority of them would save money, and thus energy, over time. This finding strengthens the case for pushing buildings to adopt energy efficient technologies. Innovation systems and related studies meant to explain how and why innovations penetrate the market emphasized that cost analysis is a primary concern of building owners. The costs, as well as the carbon footprint, can be reduced through the use of energy efficient innovations.

Because the urgency surrounding this topic is relatively recent so are the innovations in technology. Over time, increasingly efficient

[1] A. Heeger, Nobel Laureate and co-founder Konarka Technologies, personal communication, November 24, 2014.

technologies will emerge at lower costs. The case of the semitransparent PV coatings for windows is one example of a technology that is still in its beginning stages but shows significant potential.

The outlook for energy efficiency is positive. While demand for energy will continue to increase, both in developed and undeveloped parts of the world, the innovative methods of conserving energy in commercial buildings show significant improvement in the past few decades. Governments and policy makers should feel comfortable incentivizing energy efficient programs. Organizations that generate energy consumption data should continue to broaden their spectrum and further studies should be conducted to maximize the dissemination of information, both to consumers and innovators.

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CHAPTER 13

Agricultural Sector Energy Efficiency

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13.1 INTRODUCTION

The agricultural and farming industry in the United States is best framed and understood in terms of its historic relevance to the United States' current role as one of the most economically and sociopolitically powerful nations in the world. As a permanent member of the United Nations Security Council and principal invitee to the G8 summit, it is unquestionable that global affairs are affected by America's attentions, and indeed, intentions. Much of this strength is derived from the nation's historic role as an economic superpower. American industry has led to astronomical gains in prosperity for the country and its trading partners.

Agriculture and farming provide the necessary sustenance for life. The large variety of foods humans consume, be they from plants or from animals, will often originate from a business in the agriculture sector. The days of small, locally operated, family farms in the United States are nearly gone and large conglomerates now provide greater efficiencies and output.

In the 21st century, a unique phenomenon has taken place. In the United States, the largest crop sold by volume and by market value is maize (colloquially understood as corn). This single crop now plays a substantial role in the U.S. economy. The United States is, by a significant margin, the world's leader in corn production, and perhaps even more shockingly, the country exports nearly 20 percent of the crop to other countries. The reason for this phenomenon can be understood by considering Figure 13.1.

The ethanol product produced from corn has found popular use as a biofuel, where the corn ethanol is used as an oxygenate in gasoline. The sustainability of corn-based biofuels is a critical topic of discussion. Furthermore, while the corn biofuels may improve the energy efficiency of vehicles and reduce the carbon footprint of the transportation sector, corn is a notoriously energy-intensive crop. The energy efficiency gained in an automobile is offset by the porous energy efficiency lost on farms.

This single example is one of many that should indicate that the agriculture sector cannot be understood without examining the role the energy sector plays in it. The concern of this chapter will be on applications and effects of energy efficiency in the agriculture sector. The chapter will first briefly examine the historic importance of agriculture in the United States from its founding in 1776 to the Great Depression and introduction of farming subsidies, and to the present day. It will then review a number of publications and research studies into the topic. Finally, the chapter will conclude with the current and potential future state of energy-efficient technologies in the agriculture sector and a call to action for more research to be conducted.

Climate change and the environment's sustainability must be balanced with consumer needs in agriculture and in energy. The agriculture sector,

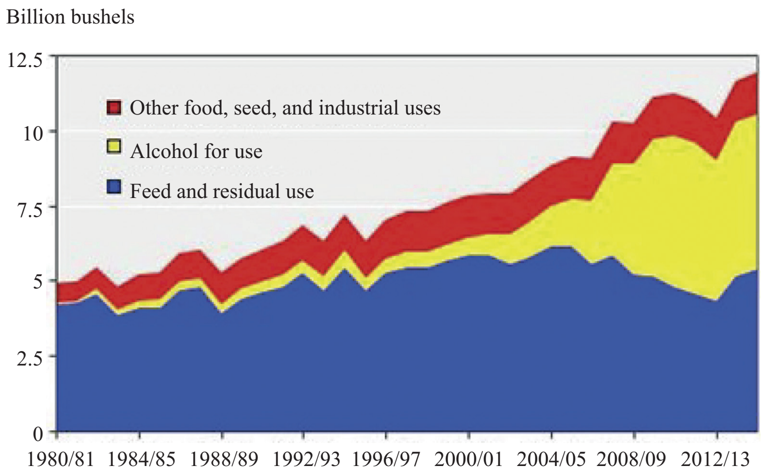

Figure 13.1. United States' domestic corn use (2014) [1].
Source: Calculated by USDA, economic research service.
Updated: October 2014.

by definition, will require a large land mass and have a significant impact on the environment. It is the hope of this chapter to stimulate a responsible conversation about the symbiotic relationship between agriculture and energy efficiencies and responsible treatment of the environment.

13.2 OVERVIEW OF AGRICULTURE IN THE UNITED STATES

Though the economic strength of America is currently provided as a service economy, defined as an economy predicated on providing intangible economic goods as opposed to tangible commodities, the historic economic strength of the nation, from its founding in 1776, appeared from agriculture, defined as the growing and care of fauna and flora for eventual consumption (2003) [2]. The combination of fertile soil, ideal climate conditions, and, perhaps most importantly, the slave trade allowed the U.S. farming industry to prosper. As described by former Agricultural History Society President and Stanford economist Gavin Wright, it is evident that much of America's success came by accident (ideal physical and climate conditions) and by forced labor. Though many would claim that America's success is due to a variety of factors, its true success comes because the cost of labor for many industries was effectively zero. Many crops, especially cotton, though also tobacco and wheat, achieved incredible yields because the cost of production was dramatically reduced (2003) [3].

Following the Civil War and Western Expansion, costs of American farming increased; however, due to advances in technology and increase in global demand, revenue losses were somewhat offset. The introduction of soybean in the early 20th century created a new cash crop for the United States and, by the mid-1940s, the United States was the world's leading producer of soybeans (2012) [4]. The agriculture sector increasingly became a critical component of the U.S. economy.

In the 1920s and 1930s, growth and production began to dramatically outpace demand and prices plummeted. The incidence of low prices was one of the many causes of the Great Depression and these prices were not offset until the introduction of a comprehensive agricultural subsidy program for farmers. President Franklin D. Roosevelt signed the Agricultural Adjustment Act to create the Agricultural Adjustment Administration to regulate production. Though the administration was eventually deemed unconstitutional by the Supreme Court, it laid the foundation for the Soil Conservation and Domestic Allotment Act. This act provides a subsidy to farmers to supplement their income and allow for the management of agricultural commodities. Today, annual Farm Bills are passed in the U.S. Congress to regulate and extend farm subsidies. Production is kept low through government spending to maintain a certain relationship between supply and demand and ultimately provide a price that benefits consumers and producers fairly. Currently, the United States pays approximately 20 billion dollars in agricultural subsidies a year (2012) [4].

These subsidies are critical to the global economy. According to the United States Department of Agriculture (USDA) "[s]ince the 1930's, agricultural productivity measured in crop yield per acre has more than doubled" (1983) [5]. Simply put, U.S. farms are producing more crops per acre than ever before. This has led to an increase in the fuel demands of the United States. Tractors, irrigators, and any of the numerous farm machineries require fossil fuel gasoline to operate. Synthetic fertilizers, artificial materials used to stimulate plant growth through nutrient saturation, have significant energy needs as well.

According to the 2012 U.S. Agriculture Census, there are 2.1 million individual farms in the United States occupying over 914 million acres of land. The census estimates that the total market value of all agricultural products (i.e., crops and livestock) sold is just under 400 billion dollars, representing 1.2 percent of the country's gross domestic product (2012) [6]. The nation is a net exporter of food with the largest products being, by volume, maize, cattle milk, soybeans, and wheat. Comparatively, maize is significantly higher in volume production due to the necessity of ethanol production (2012) [7].

Evidently, U.S. demands for agriculture production show no signs of slowing down. Population growth and a culture of consumption derail many efforts to reduce demand. It is with this knowledge in mind that policy makers must consider making their decisions. Rather than creating policies that will unsuccessfully manage demand, they should create policies that effectively and consciously control the means of meeting that demand.

13.3 MEASURING ENERGY EFFICIENCY IN THE AGRICULTURAL SECTOR

For policy makers to effectively make decisions regarding energy efficiency in the agricultural sector, they must first have suitable means of measuring energy efficiency. One such method has been proposed by researchers Stéphane Blancard and Elsa Martin (2013) [8]. Energy efficiency is, traditionally, given by the ratio of energy output to energy input, a claim supported by Dr. K. V. Wong in the second edition of his well-regarded textbook *Thermodynamics for Engineers* (2012) [9]. As such, in the agricultural sector, using the aforementioned definition, one would measure energy efficiency for a bushel of corn as the amount of energy required to produce a bushel of corn.

When the data are readily available, this is a very effective methodology. Unfortunately, the agricultural sector, as a rule, is not forthcoming with efficiency information. Transparency between the government and private sector is small, most likely due to the large incentive to hide potentially low energy efficiencies so as to meet environmental regulations and maintain subsidy qualifications. Therefore, the researchers mentioned earlier attempted to consider various uncertainties when computing energy efficiency of a farm. The method used is Data Envelopment Analysis (DEA). DEA utilizes linear programs to construct nonparametric production frontiers (i.e., data without the use of probability distribution). This alternative form of measuring energy efficiency can be described in simpler terms as the ability to produce a given unit of output using a minimum level of energy. With this new definition, for example, a farm with 100 percent energy efficiency is able to produce one bushel of corn with one unit of the energy minimum.

This methodology is a relatively new area of study. The use of DEA in the agricultural sector and this new energy efficiency definition has only been considered since the mid-2000s (2013) [8]. Therefore, while the method is promising, it cannot replace the traditional method as of yet. The traditional method, defined by Wong and others, is a safer approximation for policy makers.

This traditional method can be shown its effectiveness in the following study from researchers C. J. Swanton, S.D. Murphy, and others. The researchers studied energy efficiency programs and defined energy efficiency as energy use per ton of crop produced (1996) [10]. By this method, they found that energy efficiency could be increased by decreasing energy use from inputs like fertilizers and machinery operations or by increasing the crop yield output. This simple idea is very powerful. It enables policy makers to clearly see the two ways to increase energy efficiency in the agriculture sector. Therefore, this report makes use of this definition for energy efficiency. Though transparency is an issue, a concerted effort to require proper reporting from the private sector will enable it to have widespread use.

13.4 IMPROVING AGRICULTURAL SECTOR ENERGY EFFICIENCY: DECREASING ENERGY INPUTS

Energy efficiency in the agricultural sector can be improved by decreasing the energy inputs. The management of tillage methods, pesticide use, and fertilizers all play a significant role in the energy balance of the farm system. Once such method to decrease energy input is to improve fertilizer use and manufacturing. Nearly 70 percent of the energy used to create a crop yield of corn is from fertilizer manufacturing (2003) [11]. Fertilizer manufacturing requires the production of a high quantity of nitrogen, which comes primarily from natural gas.

Therefore, if policy makers want to reduce the single largest source of energy input in the agricultural sector, they would be best served to regulate the fertilizer industry. Alternative raw materials could be used in fertilizer production. Phosphorus has been shown to be an effective alternate to nitrogen and, with further research, could be implemented in nitrogen's place. Another such material that has shown promise in the place of concentrated nitrogen is ammonia (1994) [12]. Energy consumption by steam reformation is the primary method for ammonia production as opposed to natural gas burning for nitrogen. Studies estimate that the energy-saving potential is nearly 6 percent. This low-cost alternative will not create a massive change in the energy efficiency of the agriculture sector; however, on a large scale, it would make significant improvement in the overall environmental health of the planet.

Another such method would be to reduce the energy input during the tillage and herbicide usage. Tillage is the preparation of land for farming. This involves a number of machines and farming methodologies. The smallest energy input possible for farming is the no-tillage farming method; that is, leaving the ground as is. However, this method often requires a large increase in pesticide use, which may increase the overall energy input (2006) [13].

The use of a plough in farming is often considered critical to high crop yields. However, the use of a moldboard plough will increase the energy input to the farm system. Moldboard ploughing involves digging a linear continuous "valley" in the soil. The plough will often run on fossil fuel or be pulled by a tractor also running on fossil fuel.

The highest energy use for tillage occurs with moldboard ploughing. Studies estimate that energy savings of nearly 10 percent could be achieved by switching to alternative ploughing techniques such as ridge-till ploughing. Ridge-till ploughing involves creating artificial ridges or utilizing ridges in nature to plant seeds. Were farmers to limit their output expectations and utilize no-till techniques, the energy savings could be as large as 32 percent (2006) [11]. Oftentimes, policy makers will be concerned with the energy expunged from fossil fuel-burning vehicles. And indeed, in crops such as soybean, which are notoriously hard and capable of high yields in poor soil, fuel consumption is the largest energy input. But many policy makers often neglect the fertilizer-related energy inputs. For corn especially, nitrogen fertilizer is by far the largest energy input for the farm.

If a farm were willing to invest a high amount of labor hours, a large quantity of corn could conceivably be produced with little fossil fuel energy. In Indonesia, for example, corn production requires approximately 634 hours of labor per hectare with zero fossil fuel input. The average corn yield in Indonesia is 1,200 kg/ha. Compare this with the United States, where corn production requires approximately 11.4 hours of labor per hectare with significant fossil fuel input. In fact, nearly 25 percent of the total energy in the U.S. corn production is consumed by fossil fuel-driven, labor-reducing machinery. The average corn yield in the United States is 9,400 kg/ha.

By these calculations, it would appear that the United States has a dramatically more efficient ability to produce corn. And by some measures, this is true. Industrial farming will produce higher crop yields. But by investigating further, in Indonesia, the economic cost of producing a hectare of corn is approximately $100. In the United States, the economic cost of producing a hectare of corn is $927. Therefore, while the United States is able to produce corn more efficiently in terms of time and pure yield, it is far more expensive to produce that much corn than by hand as in Indonesia (2009) [14].

This pattern is repeated when examining wheat production in Kenya, rice production in India, and cassava (a tuber crop resembling a potato) production in Nigeria. Consistently, the United States produces far more of the crop in a quicker time frame; however, it costs significantly more per crop to do so. The U.S. agriculture methods for many crops are simply not energy efficient when compared to the methods used in countries around the world. Policy makers should thus consider the effect various farming methods have on energy efficiency as well.

The final method to decrease energy inputs for the agriculture sector would be to encourage the selection of low-energy crop choices. Corn is a notoriously high-energy crop; however, it is also highly productive. This high productivity is due to the significant amount of fertilizers and irrigation inputs for the crop (2009) [14]. Products such as the soybean are very energy-efficient crops and a potential switch in consumption habits to soy could increase the overall energy efficiency of the agricultural sector.

13.5 IMPROVING AGRICULTURAL SECTOR ENERGY EFFICIENCY: INCREASING ENERGY OUTPUTS

Increasing energy outputs (i.e., product yields) in the agricultural industry is often a more difficult discussion than decreasing the energy inputs. This is for a number of reasons. The main reason is that many increases in production are offset by increased demands for energy input. The efficiency actually lowers for many common methods when the production is pushed to a maximum. A second reason is that the global demand for food resources is constant and very high. As such, many farms, unless otherwise subsidized, already have every incentive to maximize production. It is an area of study that is operating a peak capacity because the financial incentive to do so is great.

Despite this, there are some potential avenues for improvement. The University of Missouri and the USDA's Agricultural Research Service announced in March of this year a new soil mapping partnership and crop resource technology sharing (2014) [15]. The initiative aims to enhance sustainable crop production by targeting specific energy-neutral (meaning at no potential energy input increase) areas for farming improvement. These methods include soil selection, climate research, watershed (i.e., the amount of water the crop receives), and production conditions. Many crops are affected not only by the fertilizer but simply by the amount of rain and sun received. These renewable sources of energy can improve crop yields without requiring more energy inputs. In a sense, the partnership will value smarter farming rather than larger farming.

Another such method to improve energy outputs is to consider the specific biology of the crop. Many plants have evolved to administer a large arsenal of direct and indirect defenses to the adverse elements in the environment (2012) [16]. If advances were made in understanding the chemical composition of these crops, new and novel ways to increase production could be developed. The natural defenses of plants could be biologically engineered to act as their own fertilizers thus improving energy output while even, potentially, decreasing the need for nitrogen fertilizer.

13.6 A CALL TO ACTION: THE FUTURE OF ENERGY EFFICIENCY IN THE AGRICULTURAL SECTOR

The future of energy efficiency in the agriculture sector is difficult to ascertain. Undoubtedly, the environmental impact of agriculture is staggering and must be properly regulated if the planet is to remain inhabitable. Beyond climate change, soil erosion, crop contamination, and fertilizer infestations will have a significant effect on future generation's quality of life. One could say that citizens are obligated to explore energy efficiency in the agricultural sector because it is potentially a matter of life and death. Unfortunately, while the aforementioned is true, it is a bit piece of ironic hyperbole in light of the fact that so many other sectors are as reliant, if not more so, on fossil fuels.

The potential future state must involve more research into the following areas:

1. Alternative fertilizer composition production methods
2. Alternative tillage methods and crop biological compositions
3. Reducing the impact of corporate farming systems

First, the fertilizer compositions must reduce the amount of nitrogen necessary to produce high yields. The burning of natural gas required to create such a large amount of nitrogen is harmful to the environment and energy inefficient. Artificial saturation of nitrogen may produce higher yields of crops; however, it is potentially irresponsible and even, as earlier mentioned studies showed, cost ineffective. As discussed previously, 70 percent of corn energy inputs come from fertilizer production and use. This should be unacceptable. Policy makers must consider the effect these chemicals have on the planet as a whole.

Second, alternative tillage methods must be considered. While moldboard ploughing is an inefficient tillage method by energy efficiency, it does produce a very large volume. As such, it may be a reality that future generations are forced to deal with, especially if the corporate farm model does not dissipate. That being said, investigation into alternative energy machinery could have a large beneficial effect on tillage methods. Perhaps, solar-powered tractors or fuel cell–powered ploughs are ideas to consider for the young bright engineer. Likewise, this young engineer should also consider investigating the biological composition of crops and if the cellular and molecular levels of the plant can be manipulated to improve yields. These methods would reduce energy input and increase energy output, ultimately increasing the energy efficiency.

Third, consideration must be made toward reducing the corporate farming system in America. As is shown by a number of studies, the local farming model, where families grow enough for their small community's consumption is far more energy and cost-efficient than the large-scale model currently in place. At the very least, more regulation is needed to reduce the extreme energy inputs currently in place. World hunger will not be solved by overproducing food stuffs. Only by smarter farming and smarter use of energy can the issue be solved.

The United States is a leader in global agriculture. This role comes with a great opportunity but also a great responsibility. Elected officials and policy makers must consider the effects energy inefficiencies in the sector are having on overall production and on the environment. It is the obligation of this country to lead the world in proper energy-efficient agricultural practices.

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INDEX

Essays in Energy

Kaufui Vincent Wong

Essays in Energy is a collection of a number of essays by the same number of engineers. They show a variety of viewpoints and diversity. This collection is meant to incite and excite conversation among engineers, scientists, and society at large. It would serve as a catalyst for a three-credit course as an introductory engineering subject to non-engineering university students. As university education develops to better prepare future leaders to appreciate science, technology, engineering, and mathematics, engineering courses for non-engineering majors are essential and so is the requirement of worthy textbooks.

This monograph intends to be one of the useful tools available. The wide range of topics includes nuclear power, small hydroelectric plants, wind turbines, and organic photo-voltaics. Nanotechnology, natural gas, and deep sea oil drilling are presented as well.

Kaufui Vincent Wong grew up in Malaysia and came to the United States in 1973. As a young man, he had four parts of a wish. He accomplished the third part of his wish when he started as a professor at the University of Miami, Florida, in 1979, and that was to teach young men and women from all over the world to become engineers. He started having the fourth part of his wish come true when, in the year 2000, he published his book for students studying to be engineers. By 2012, he has already published four textbooks. The current book represents his fifth book. He has authored well over 200-refereed technical papers. His mass media teachings are well received. He strives daily to be a better communicator and to do good for society.

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