Potential of Wind Energy in the United States

An Interactive Qualifying Project

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by

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Abstract:

This report investigates the role which wind energy plays in providing power to the United States, and the likelihood of this role increasing in the future. The motivating factors for such an investigation include the inevitable depletion of fossil fuels, need for US energy independence, and the reduction of CO_2 emissions. By closely examining both the current state of energy usage and wind technology in the US, the potential for future growth of wind based power generation is firmly established.

Executive Summary:

Over the past several years, wind energy has experienced a significant amount of growth and has exhibited the potential for continued expansion and success in the electricity generation market. The current energy infrastructure in the United States is overwhelmingly dependent on fossil fuels. There is an increased urgency to develop renewable energy technologies in order to reduce harmful emissions from fossil fuel sources and achieve stable energy prices.

Upon modeling the future electricity production from the United States top energy sources (coal, natural gas, nuclear power and hydropower), it was determined that of the current renewable energy sources, wind energy has the most potential to immediately provide reasonably priced and emission-free electricity. All facets of wind energy are explored beginning with the wide variety of design options, including the use of wind capture from basic land based turbines, to offshore and high altitude turbines. The mechanics of turbine operation and the physics of wind harvesting are discussed in order to understand how energy is captured and transformed. This also leads to an understanding of the performance regions and the maximum power output for a given design.

A wide range of modern issues concerning wind energy are discussed beginning with the prospects of storing excess energy so that it is not wasted in times of low demand. Operating issues such as turbine noise and the feasibility of residential small scale turbines are discussed with real world examples. The optimal strategy for the success of wind energy is later explored based on the actual wind energy resources in the United States, as well as current and future programs including tax incentives, portfolio requirements and carbon costs that can make wind energy prices more competitive with traditional generation sources.

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Section 1: Introduction

As we approach the end of the first decade of the 21st century, the fundamental question of where and how we obtain our energy supplies is increasingly in need of a long term answer. This is by no means only a recent question, though. The United States has been forced many times before to cope with energy crises resulting from anything from supply bottlenecks to political stand-offs abroad. Fortunately, albeit temporary, solutions have been found to make ends meet. The underlying problem, though, of keeping up with our nations' insatiable energy consumption still remains and has become even more complex over time. At the heart of this issue has been our increasing dependence on foreign petroleum resources, mainly crude oil. In approximately 50 years, the nation has gone from being almost completely self-sufficient to importing over 65% of the oil it uses (1). As consumption continues to rise, this alarming trend is certain to continue at least into the near future. As to why our goal should focus on reducing petroleum dependence, there are three main answers.

Perhaps the most clear-cut reason for reducing oil consumption is simply resource availability. Oil as a natural resource is finite and is not naturally created at any rate near to what it is consumed at. This means that over time we have been depleting the total quantity of this resource, which is referred to as the "ultimate recoverable reserves", and continue to do so at an increasing rate. The question of how long our current supplies will last is very complex, depending on many factors such as growth in demand, improvements in recoverability, new oil discoveries, and certainly market price. In general though, even the most conservative estimates predict that the global supply will reach a peak before the end of this century. The peak refers to the point when production can no longer be increased, due to economic and technological limits, and either flattens or begins to decline. More likely scenarios, which will be addressed in the overview section, predict the peaking of oil to occur earlier in this century, however. Regardless of when exactly it occurs, the fact that it will occur in the near future is a very serious threat to our current petroleum-dependent economy and lifestyle. As this point nears, the economic side effects of supply shortage and rising prices will be disastrous if we are still as highly dependent on oil as an energy source. The potential effects of supply shortages alone can bring a modern economy like that of the United States to a near halt because of how crucial this energy source is for transportation, industrial and commercial uses, and heating. Even if supply shortages do not become an issue as soon, the rising prices associated with keeping up production levels could quickly make most consumers unable to afford the quantities that they have been using.

A second major reason is the connection between dependence on foreign petroleum imports and political and economic security here in the US. The amount spent on oil imports totaled nearly $500 billion in 2008 alone, which made up approximately 25% of the value of all US imports for the year (1). With increasing amounts of wealth being sent overseas, The US is putting itself at an economic disadvantage by adding to its already large trade deficit. Perhaps more importantly, relying on foreign nations for such a vital resource makes the major parts of our economy which use petroleum also dependent on these other nations. This means that any issues affecting supply and production abroad will also have direct consequences here in the US. Furthermore is the fact that some of our largest petroleum suppliers are nations not in the best political relations with the US. The fact again that we are dependent on them gives them political leverage against us in any contested issues between the two nations.

In perhaps what is the most important issue in the long term, the combustion of petroleum as an energy source is the major contributor to greenhouse gas emissions, mainly carbon dioxide.

Since the beginning of the industrialized age, and consequently the large scale use of petroleum, carbon dioxide levels in the atmosphere have rose continuously to record levels not present for hundreds of thousands of years. The well known greenhouse effect of carbon dioxide acts to insulate the Earth and is responsible for keeping its temperatures at their current habitable level. However, with the addition of so much extra carbon dioxide to the atmosphere over the last 200 years, this insulating effect has also increased, leading already to a rise in global average temperature. So far, the impacts of warming on the global climate are not fully clear, though there certainly have been significant changes to many weather related trends. The potential future effects, however, are predicted to be much more drastic than anything seen so far. Although the setup for truly dramatic changes has already been put in place by past emissions, reducing future emissions will certainly help to lessen the severity of long term climate changes.

1.1 Prospects of Increased Renewable Energy Usage

With over 75% of the total energy usage in the United States coming from petroleum sources (oil, coal, and natural gas) (1), there is much room for increased use of renewable energy sources. People in America and across the world are intrigued by these renewable energy sources because they produce none of the harmful emissions (carbon dioxide, sulfur dioxide, nitrogen dioxide) that fossil fuels do, and are able to run on a fuel that is free, abundant, and practically limitless (whether it be the sun, wind, or flowing water, to name a few). There are many renewable energy sources that are in use across the globe, but these technologies need to be refined and made to work more efficiently if they are to ever replace fossil fuels as the main energy providers of the world. The main question then becomes how renewable sources can be used to alleviate the previously described problems associated with petroleum use. The most direct use of renewable sources would be to add production capacity to the electric grid. This is certainly needed right now and will increasingly be necessary to keep up with growing electricity demand. Using renewables in this way has several benefits. Primarily, it addresses the issue of greenhouse gas emissions that are present with all petroleum based methods of electricity generation. Although petroleum based generation will still be needed to supply US electricity demand in the near future, renewable sources could be used to supply a major portion of all new generation capacity.

A major issue that arises is that almost all oil use goes towards sources other than electric generation. These include transportation, industrial applications, and residential heating, with transportation consuming 70% of all oil used in the US (1). Unfortunately, these consumption areas can't directly use renewable energy sources as a substitute. Instead, shifts need to be made from fuel based sources to electric generation sources. Two solutions to the transportation energy issue are possible, though. Of the main petroleum sources, the supplies of coal and natural gas still originate primarily from the US, as compared to oil, in which a majority is imported. Also, both coal and natural gas still have enough proven reserves to significantly outlast oil at the current consumption rates, giving them another advantage. One possible solution is through the direct use of natural gas for transportation, which currently supplies about 2% of transportation energy use. The opportunity here for renewable sources would be to replace the electric generation currently provided by natural gas, freeing the natural gas to play a larger role in fueling transportation. Another possible solution would be through the large scale production of hybrid plug-in or all electric vehicles. Although these technologies still need significant development, we are at the point now where they're starting to be produced for sale in niche markets. If they are able to supply a significant portion of mainstream transportation needs in the future, then renewable energy sources can again play a part by generating the electricity to power these vehicles. In this situation, energy demand would be shifted away from oil based liquid fuels and onto the electric grid. At this point, renewable sources could then be directly used to generate the additional capacity on the electric grid needed to charge the vehicles. The possibilities of both these scenarios will be explored later in detail.

1.2 Motivations & Goals

Christopher Lehrman:

Due to the finite nature of most of the nation's current energy sources, the potential applications of renewable energy sources seem destined to grow significantly in the near future. Whether or not this opportunity will be fully taken advantage of still remains a question. One of the main focuses of this project will be to provide insight into how we can assure that the answer to the previous question is "yes". With this, I believe that it is important to increase our knowledge and understanding of renewable energy, with the goal to improve the nation's energy portfolio. This knowledge can be improved both from increased technology and engineering capabilities and also a better understanding by society of the underlying problems and their possible solutions. The latter is my motivation for this project, which will seek to analyze the current energy situation in the US and propose uses of wind energy sources to help improve our nation's energy standing. By presenting insights to society regarding the future improvements that can be made from wind energy use, I feel this project is highly qualified as an IQP, as it will provide society with information that can be used by individuals to make educated energy decisions in their own lives.

As a mechanical engineer and physics minor, this project will be able to directly tie into my course of study by examining some of the engineering and technological advancements that are increasing the power and economic viability of wind energy systems. As I continue to pursue my degree, I hope to be able to further my understanding of energy technologies as a whole, and be able to apply engineering skills to continue the development and use of renewable energy resources. It is my hope that this project will serve as a solid foundation on which to continue this pursuit.

Nicholas Bloksberg:

I was very interested in doing this project because I saw how important it was to our society and I understand the need for new insights and fresh ideas to help solve this problem. I also wanted to get involved with this project because it ties in deeply with my course of study and career goals. As an Environmental Engineering major I have encountered material in class that has directly applied to this project. While topics that I have learned in classes will undoubtedly help me in completing this project, the knowledge and experience that I will gain from it will be even more helpful to me when completing the rest of my collegiate studies and beyond. The completion of this project will be invaluable to me in my career as I could very well be dealing with issues directly related to this topic. A successful completion of this project will improve my research and my writing skills as well as provide me with a great deal of detailed information about a wide range of alternative energy sources. I will undoubtedly be better qualified to get a job in Environmental Engineering for working on this project.

This project qualifies as an IQP because it is so crucial to the future of this country as well as the world. I hope that through much research and calculation I am able to produce some real original and useful ideas that will help to improve renewable energy technologies and make it more feasible for them to be put into use both locally and globally. In this project I will explore the worlds' current energy situation and the problems with it, especially our over-dependence on fossil fuels. I will then investigate the current forms of alternative renewable energies in use today and point out how they work, how useful they are, and how they can be improved. I hope to be able to show that wind energy has the greatest potential to be used immediately and make a significant jump in the amount of energy obtained from renewable sources.

1.3 Project format

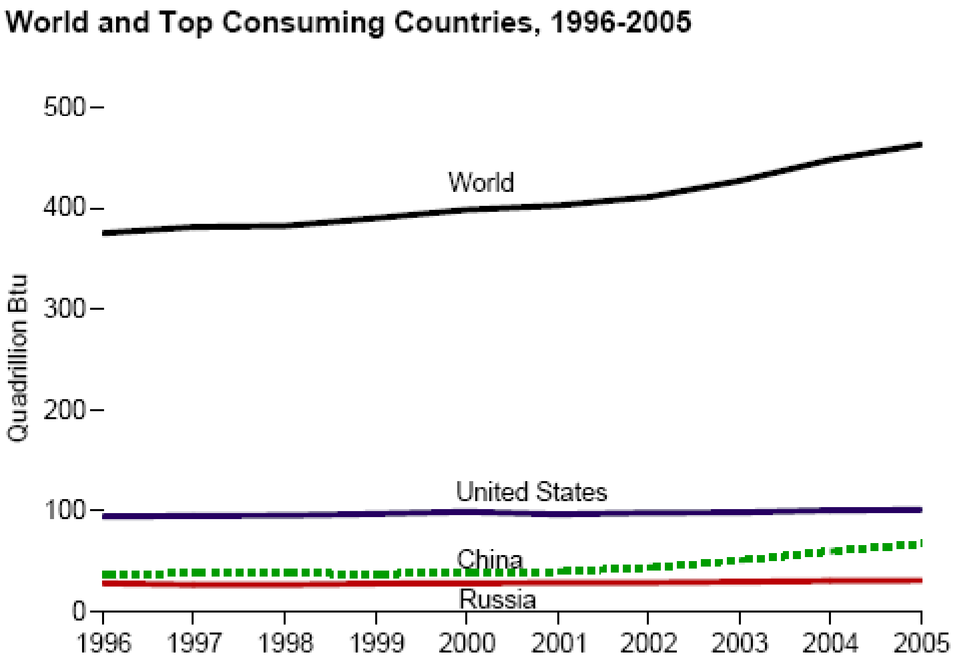
The layout of this project consists of three main parts, all with a primary focus on the energy usage within the United States. The first section seeks to overview the historical and current energy situation and examines the different sources and end-uses of energy. Much consideration is given to the supply and availability of our current fuel sources for both electricity generation and transportation. The second section is an in-depth analysis of wind energy technologies and the potential wind resource. Emphasis will be placed on the advantages and shortfalls of the technology, and also its economic competitiveness with traditional energy sources. The third section will seek to develop a strategy for using wind energy in order to reduce the need for petroleum based fuels. The changes that will need to take place in both electricity generation and transportation energy use will be looked at closely, along with the roles of economics and government policy. Finally, the impacts and benefits to society from the increased use of wind energy will be considered.

Section 2: US Energy Background

2.1 Overview

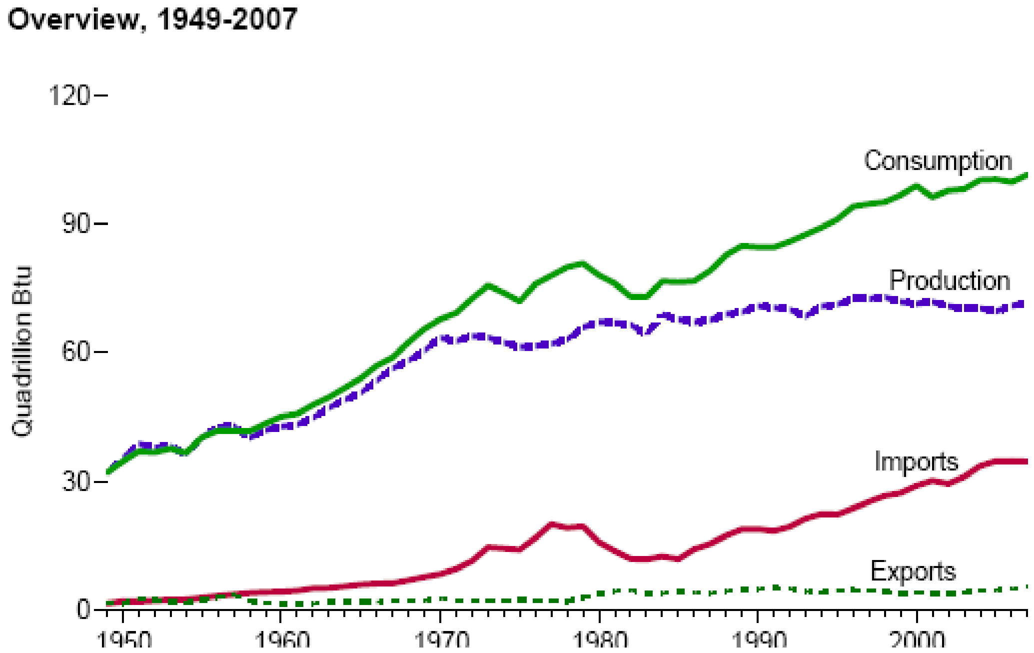
The United States is the single largest energy consumer of any nation in the world. In 2006, about 21% of the total world energy produced was consumed by the US (2). When compared to its share of the world population, which was only 4.6%, a large imbalance can be seen (1). Interestingly however, there has been a negative trend in the US's share of global energy consumption. This is due to the fact that US consumption has grown slowly compared to other large nations, while world total consumption has grown significantly.

Figure 1: World and Top Energy Consuming Countries, 1996-2005 (18)



In 2008, total US energy consumption measured 99.3 quadrillion Btu (18). Of this amount, approximately 74 quads came from domestically produced energy sources and 33 quads were from imported energy, with the difference of 7 quads due to energy exports. Looking at a history of US energy use, one disturbing trend stands out. That is the difference between total consumption and domestic production, a quantity which has been increasing since the late 1960's. As can be seen, the root of the problem is the relatively small growth in domestic production over this same time period. So in order to compensate for the growing difference, imports have consequently increased.

Figure 2: US Energy Overview 1949-2007 (19)



The next important area to look at is the overall source and end use of energy in the US. These statistics will help in determining how much and for what purposes renewable energy can be used to decrease dependence on fossil fuels. The major energy sources in the US can be put into 5 categories: petroleum (mainly oil), natural gas, coal, renewables, and nuclear power. This energy is then used by 4 main consumption areas: transportation, electricity generation, industrial, and residential and commercial. Below are two flow diagrams (1) illustrating the overall origins and end use of energy in the US in 2008; units are in quadrillion Btu. The differences between the data in the two charts is due to the fact that electric energy is not separated out in the green flow chart, while the arrow diagram has separated out electric energy production from the other three demand sectors.

Figure 3: US Energy Production and Consumption (1)

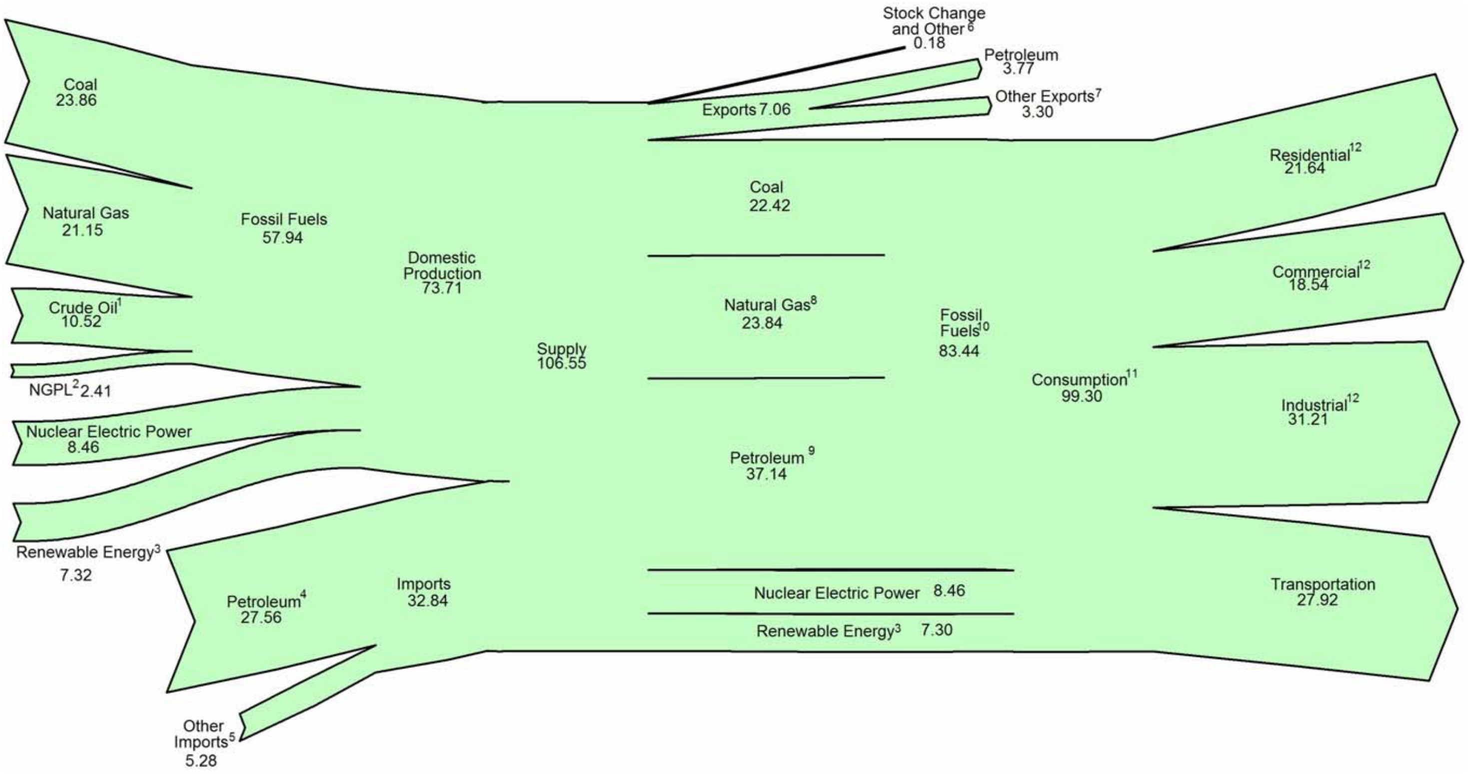
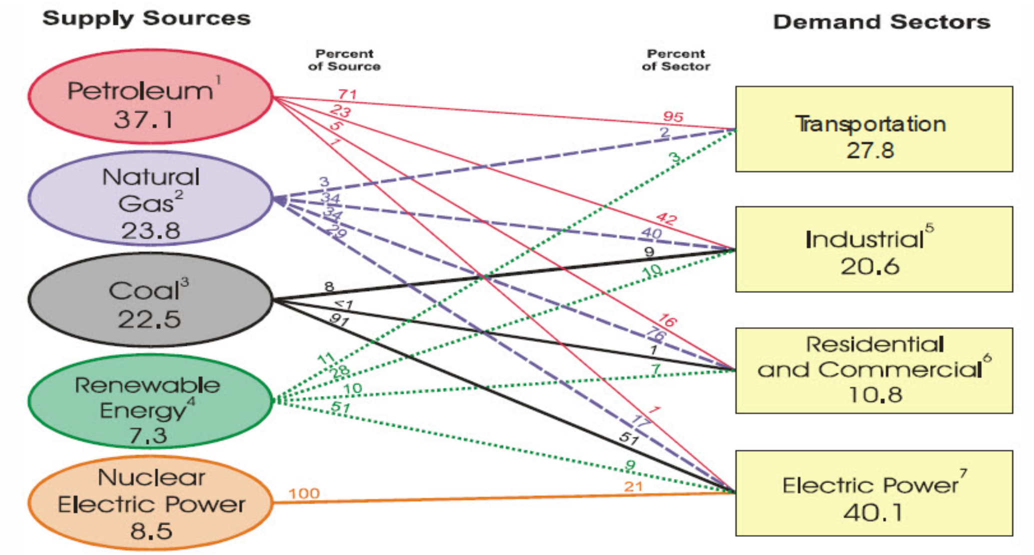


Figure 4: US Energy Demand by Sector and Source (1)

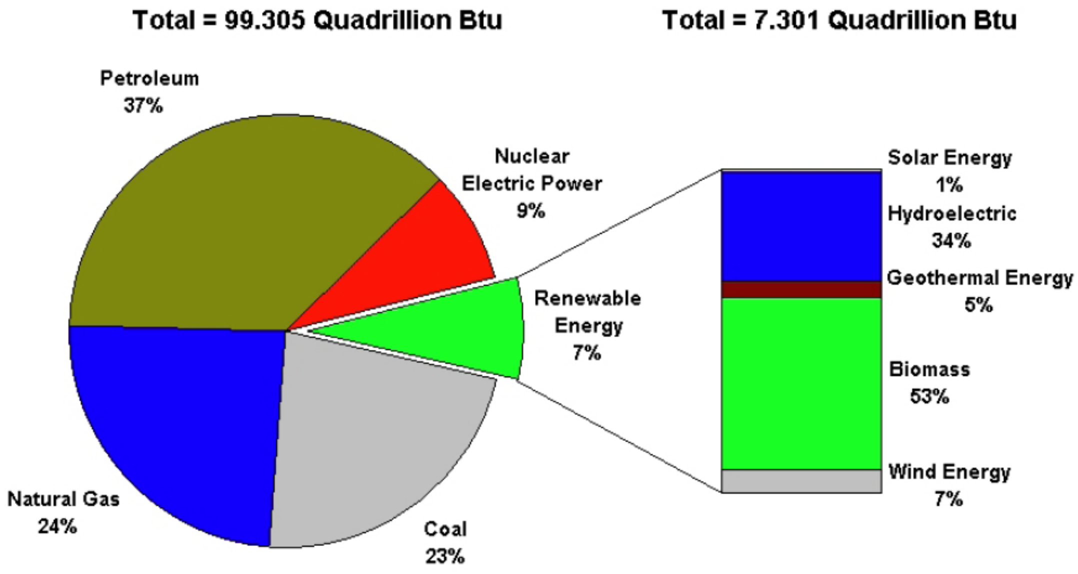


[1] Does not include the fuel ethanol portion of motor gasoline—fuel ethanol is included in "Renewable Energy."
[2] Excludes supplemental gaseous fuels.
[3] Includes less than 0.1 quadrillion Btu of coal coke net imports.
[4] Conventional hydroelectric power, geothermal, solar/PV, wind, and biomass.
[5] Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
[6] Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
[7] Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public.

Looking at this wealth of information, it is a good time to further analyze the potential uses of wind energy generation. Earlier, the fact the wind energy cannot directly replace the uses of all fossil based fuels was discussed and some possible scenarios were laid out. Now it can be seen just where wind energy can be used in the energy supply mix. At the simplest level, wind energy acts as a source of electric generation. Therefore, the ideal scenario for the advancement of wind energy would be to replace all fossil fuel sources of electricity generation. Looking at the second chart, we see that 70% of electric generation does in fact come from fossil fuels, with practically all of that consisting of coal and natural gas. Wind energy would be a direct substitution of these sources, and therefore could hypothetically replace this 70% of electric generation, totaling 28 quadrillion BTU. The second scenario considered previously was that of using wind energy to power the transportation sector. In this scenario, the widespread deployment of electric vehicles would be a prerequisite. If this were to become reality, then the energy demand of all these vehicles would be shifted to the electric grid, and again wind energy could potentially be the supply source. Looking at the second chart, we see that the transportation sector consumes about 28 quad BTU total. Now personal vehicles aren't the only end use in this sector, but they make up the majority at about 64%, with the rest consisting of aviation, marine, and heavy vehicle/equipment use. Again, wind energy could then hypothetically replace 64% of the transportation sectors energy supply, totaling approximately 18 quadrillion BTU.

2.2 Prospect of Renewable Energy

<u>Figure 5: Renewable Energy Share of Total Energy Consumption in US, 2008 (1)</u>



From the chart above you can see that the vast majority (about 84 percent in 2008) of the energy consumed in the United States is from fossils fuels. These fossils fuels have effectively provided energy to this country for many decades, so why now is there such a push by the public and government alike to develop and integrate renewable energy sources into the infrastructure? Many of these energy sources have been in use for hundreds of years, like wind and hydropower for pumping and primitive solar heating. The reason that these technologies have not become main stream in America and around the world is because coal, natural gas and petroleum products have proved much more cost effective and easier to obtain. Currently though, as the demand for energy continues to rise, many consumers are weary of fossil fuels as their costs are going up and they continue to pollute the air. In the 1970's, when the first and second Arab oil embargo made gas prices skyrocket across America, the government had interest in developing renewable sources of energy[2]. This interest started to fade in the 1980's and 1990's and although there was continued research and development, the renewable energy technologies were put aside because they still remained too expensive when compared to the fossil fuels. Over the past decade, America has seen fuel prices fluctuate, and escalate to as high as they have ever been. Once again these alternative fuels are becoming economically relevant and thus the market for them is growing. With both State and Federal Governments giving incentives toward the use and development of renewable energy technologies, continued growth over the next several decades can be expected (1).

Figure 6: Global Investment in Renewable Energy, 2004-2008 (3)

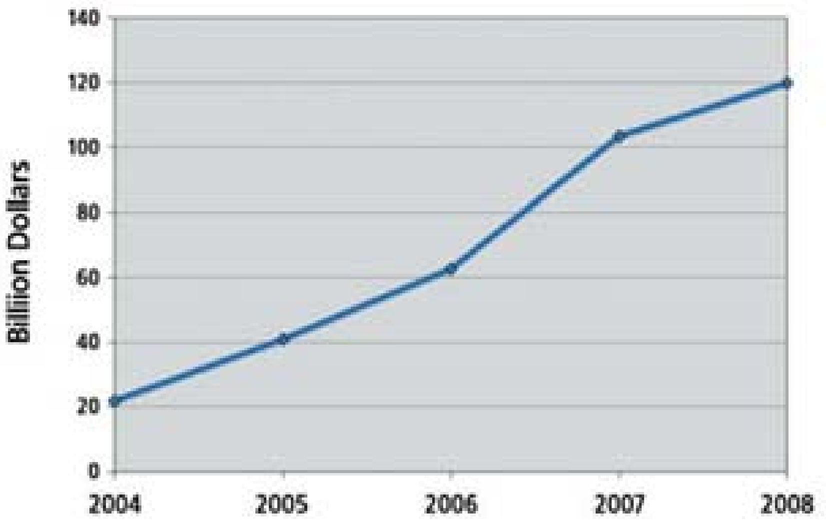


Figure 7: Oil Prices, 2001-2009 (4)

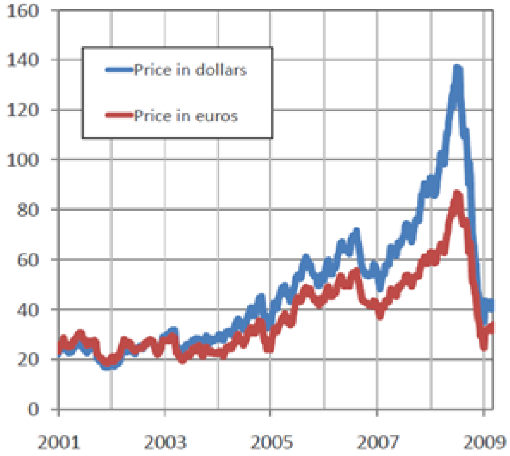
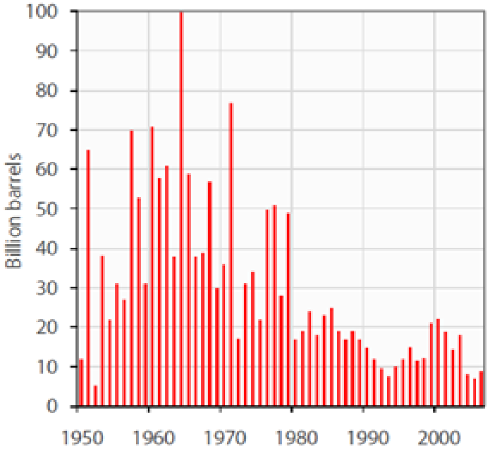


Figure 8: New Oil Discoveries: Historical Trend (4)



There are five main types of renewable energy sources currently in use: wind, solar, hydroelectric, geothermal, and biomass. The following is a brief overview of each of the technologies.

2.2.1 Hydroelectric

Humans have been using hydroelectric power in the form of water wheels for over 2,000 years. Hydroelectric power generation is the process of harnessing the water's energy as it flows from a higher to a lower elevation. This is a great source of energy because it's completely renewable in the sense that there will almost always be water flowing, and of course it is free beyond the initial construction and subsequent maintenance costs. In 2008, hydroelectric power accounted for 34 percent of the total renewable energy produced in the U.S. One problem that hydropower can cause though is that the introduction of a hydropower dam can damage marine ecosystems and sometimes wipe out an entire fish population by blocking upstream migration (8). A hydropower dam can also affect oxygen levels enough to reduce water quality and kill fish that swim into the turbines. Also, an effective hydropower plant can only be built on a certain spot that has the right conditions and enough flow to make the generator feasible. Hydropower has been one of the leading renewable energy providers in America for many years yet its progress is slow compared to other renewable options. Hydropower should continue to be a solid and efficient energy provider for many years to come, however, each year fewer plants are built because sites are running out (7). Of all the renewable energy sources, hydropower is the most mature currently and thus it will not be expected to show much further advancement in terms of improved efficiency and new generation capacity.

2.2.2 Geothermal

In 2008, geothermal energy provided 5 percent of the total renewable energy consumed in the U.S. Geothermal energy comes from hot water or steam reservoirs deep within the Earth. To extract energy from the water or steam, a well is built and a steady flow is pumped and then used to provide the thermal energy input for a traditional steam turbine unit. Geothermal is an effective way to produce energy; however, it is limited by the fact that plants can only be built on specific, suitable sites. These reservoirs of underground energy are not abundant or easy enough to find as would be necessary for this technology to make the leap from minor contributor to major producer of electric power. Geothermal energy is expected to slowly and gradually rise over the next several decades as more sites are found and the process is made more efficient, however, it is still expected to retain only a fraction of the electric energy market (9).

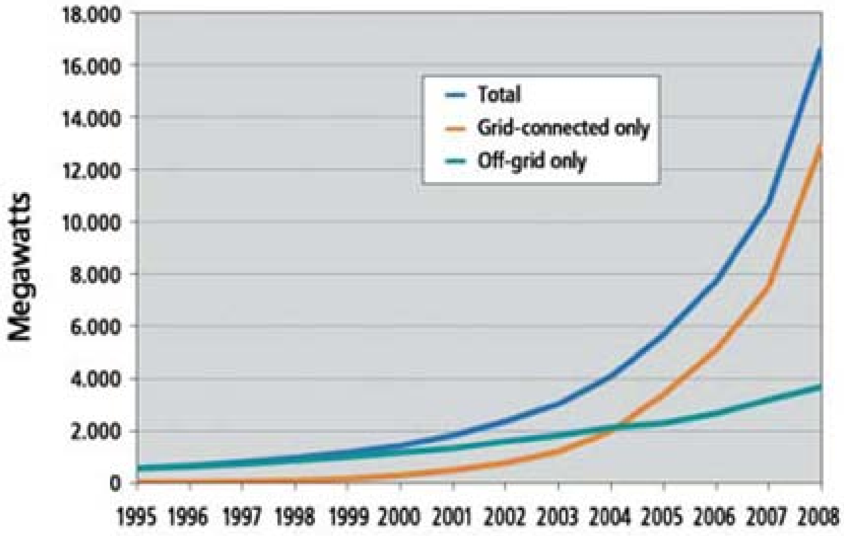
2.2.3 Biomass

Biomass provided 53 percent of the renewable energy consumed in 2008. Of this 53 percent, wood accounted for 28 percent, fuel ethanol and biodiesel biofuels accounted for 19 percent and the remaining 9 percent was from solid waste, landfill gas, sludge waste, agricultural byproducts, and other biomass. The term biomass encompasses many different categories. In general, biomass is defined as “all non-fossil material of biological origin (10).” The burning of wood to create energy has been in use in America for hundreds of years and it should continue to be an energy contributor into the future. There is an inherent limit on the potential of wood energy, due to the quantity of trees available and the need for trees to provide oxygen. Ethanol and biodiesel fuels derived from organic material are also cost effective options, but there is only a limited amount of biomass available that can be used to produce them. Power from waste and landfills can also efficiently produce fuels that can generate power but they are limited by the fact that they take up a lot of land and can take a while to produce the gases. Biomass will continue to grow and be a factor in renewable energy production; however the total potential for biomass, especially as an electricity generator, is not nearly as great as other sources like solar and wind. (11)

2.2.4 Solar Energy

In 2008, solar energy was only responsible for one percent of the renewable energy produced, meaning that solar accounts for only 0.07 percent of total energy consumption. Currently, the impact of solar energy is very small due to the fact that the price of solar energy today is still not near to being competitive with other energy sources. There is hope for solar, however, as evidenced by the immense growth in the field over the past several years as shown in figure 9.

Figure 9: Solar PV, Existing World Capacity, 1995-2008 (3)



Solar energy can be converted to electricity or heat and can be utilized in several types of systems. Currently, solar power systems are not nearly as efficient as other energy sources and the price is still not competitive for large scale electric generation (12). Solar energy has been used somewhat effectively for heating and other small-scale operations, and it has potential in hybrid systems alongside a wind turbine or turbines which will be discussed later. Solar power has however experienced huge growth over the past several years and continued technological breakthroughs could make solar competitive in the near future.

2.2.5 Wind Power

Wind power has been used for hundreds of years, powering windmills to pump water and grind grains (5). A wind turbine is the current day version of these windmills, and its blades harness the wind's kinetic energy to make electricity. Despite being third in size of the 5 technologies in terms of number of BTUs produced in 2008 (Figure 5), wind power may be the most relevant of all the technologies right now. Currently, wind energy is not only one of the more affordable renewable options, but it also has the potential resources to power a huge number of homes and businesses. There are still some standing problems with wind power however. Although wind is free, there is still significant cost in developing a commercial scale wind farm. In addition to the upfront costs for site planning, design, materials and installation, there are operations and maintenance costs, property taxes and insurance, as well as power delivery costs. There is also an inherent issue with the reliability of the power source (13). What happens when there is no wind blowing in a certain location? This issue of intermittency, as compared to fossil fuel power plants, where the output can be guaranteed over a certain time frame, is an obvious disadvantage of wind power which will be discussed later. To minimize this setback, a turbine should be put in an appropriate area to maximize its potential and efficiency. Often, wind flow is best in areas remote from population centers, but with turbines isolated from the cities where the power is being used, integration with the power grid usually becomes more difficult and expensive. Other problems with wind power are that it can generate noise that can disturb nearby homes and businesses, turbines can be visually unpleasing, and wind turbines have also been known to kill birds that fly into the blades (14). Wind power does offer a good amount of variety in its applications, as scientists continue to think up new ways to harness wind, such as offshore turbines, high altitude turbines and low speed turbines. Overall, wind power is a technology that is growing and continually improving, and with the right advancements, it could have a major impact on how America is powered. Because it has such great potential and has shown so much improvement over the past several years, this paper will focus on wind energy and how it can help to improve America's energy portfolio.

Figure 10: Wind Power, Existing World Capacity, 1996-2008 (3)

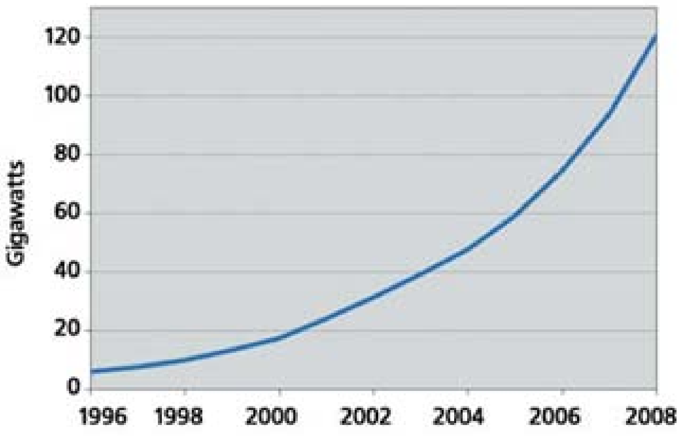
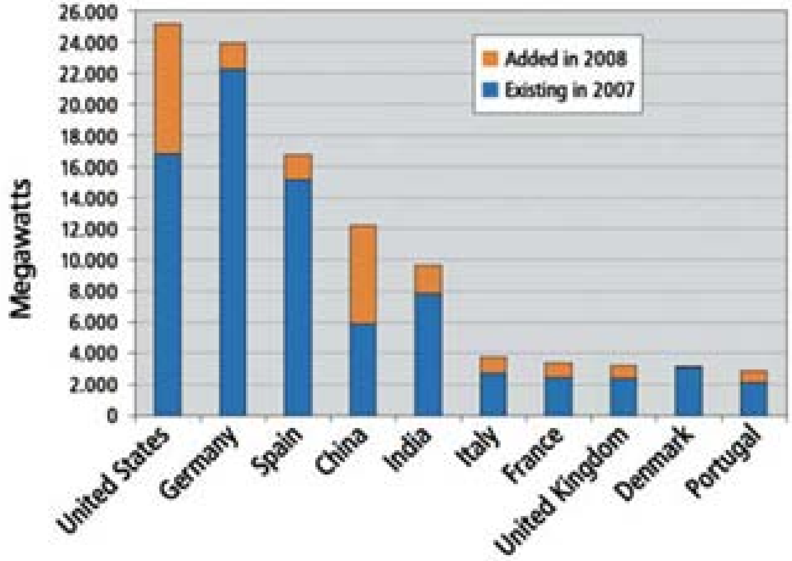


Figure 11: Wind Power Capacity, Top Ten Countries, 2008 (3)



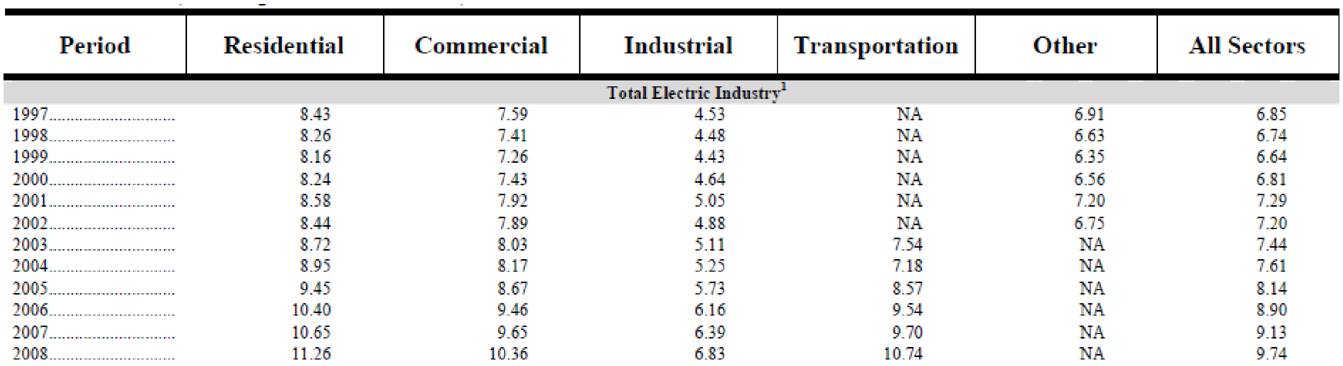
2.3 Energy Outlook

The future of energy is somewhat uncertain and there are many out there making predictions concerning future production, consumption and prices etc. One particular report that will be used as a reference is Exxon-Mobil's recent Outlook for Energy report that predicts energy numbers up to 2030 using several different scenarios (16). That study used data that has been accrued for over one hundred years in some cases, and used the trends in that data to predict the world's energy status up to 2030. The analysis is very detailed and includes data from approximately 100 countries, 15 demand sectors and 20 fuel types. This outlook makes assumptions concerning global population, economic output, energy demand, and energy supplies in order to attempt to correctly predict the energy outlook for the next couple of decades. In 2005, 245 MBDOE (million barrels per day of oil-equivalent energy) were used worldwide and were spread mainly amongst transportation, electricity generation, home heating and cooling, and industry. Based on the projected economic and population growth, the worldwide total energy demand is expected to grow by 1.2 percent per year between 2005 to 2030, growing 35 percent total from 245 to 310 MBDOE in 2030. This increase in demand will occur mostly in developing nations. Fossils fuels will continue to meet the majority of this energy demand, with oil, gas and coal meeting close to 80 percent of global demand through 2030. Residential and commercial use is the smallest of the major energy demand sectors, representing about 16 percent of total energy demand, or about 37 MBDOE in 2005. The residential energy demand will increase as the population increases. In 2005 the global population was about 6.4 billion people, and this number is expected to increase only by less the 1 percent per year but that will still be enough to push the population to 8 billion by 2030. With this population increase, global economic output is expected to increase 3 percent per year. The industrial sector is the next largest, and it is expected to grow at a rate of 1 percent per year, reaching close to 85 MBDOE by 2030, or 30 percent more demand than in 2005. Natural gas will show the greatest increase in this sector. Transportation is currently responsible for the use of over half of the world's oil demand. This demand is expected to rise due to a large increase in the number of personal vehicles in developing countries. In 2005 transportation accounted for 19 percent of global energy use and this number is expected to increase nearly 40 from 2005 to 2030, from 44 MBDOE to 62 MBDOE. In general, most of the growth in transportation will come from heavy duty vehicles as well as ships and planes, as opposed to light-duty commercial vehicles. It is expected that oil will remain as the dominant producer of energy for transportation at 94 percent, with biofuels (5 percent) and natural gas (1 percent) filling out the rest. The biofuels can be food-based or non-food-based, and some of the more studied biofuels are cellulosic ethanol, biomass gasification and conversion, and algae. The US is expected to continue to produce large amounts of corn-based ethanol for use as fuels, using up to 20 percent of the country’s entire corn crop. Of the main energy sectors, electricity generation will be the largest and fastest growing through 2030. By 2030, power generation is expected to demand 40 percent of the total energy. The demand for electricity worldwide is expected to experience a more than 75 percent increase from 2005 to 2030, despite gains in the efficiency of power generation. Power generation needs are met by a wide array of energy sources. Coal currently dominates; controlling 45 percent while gas and nuclear are also important as well as smaller producers like oil and renewable energy sources. The total fuel demand for electricity generation is expected to increase by about 50 percent, reaching 124 MBDOE by 2030. Coal will continue to produce the largest amount of energy, however, except for oil, the use of other energy sources for fuel is expected to increase at a higher rate. Coal continues to have the majority of the market because it is abundant and relatively cheap. Also, scientists predict that the world’s current coal reserves, which were about 935 billion tons in 2005, are enough to last close to 200 more years based on the consumption rate. Natural gas should show continued growth, providing close to 35 MBDOE by 2030. Nuclear power should also grow, and remain as the third highest producer of power. Of the renewable energy sources, hydropower, biomass, and geothermal generation are more developed and widely used today. These sources are economically feasible and will continue to grow but their growth will be limited due to natural restrictions including site availability. Solar power is currently one of the least used energy sources worldwide. At this point in the technology, photovoltaic solar power is too expensive and inefficient to be put into wide scale use, but there is much potential for solar power as both an electricity source and a heat source in time with developments in the technology.

Wind power has been a field that has experienced major growth over the past several decades, and because of this, will be the main focus of this report. Wind turbines have become more efficient with improvements in design, and wind power is becoming more and more economically feasible as time goes by. Exxon’s outlook expects that in the United States, wind power will supply about 9 percent of the total electricity demand by 2030. This 9 percent is up from less than 1 percent in 2005, with an annual growth rate of around 12 percent. These renewable energy sources are currently more expensive than fossils fuels, however, with the possibility of additional costs from carbon policies being put into place, renewable technologies could look a lot more affordable. These policies are meant to reduce damage to the environment by greenhouse gases. The most carbon intensive fuel is coal, followed by oil and then natural gas. These policies are expected to make coal lose a considerable portion of power generation, dropping to around 30 percent. The information that was just discussed was from Exxon-Mobil Corporation, and that data was obtained from careful research and much collaboration with the heads of energy departments from across the world. The predictions are not a guarantee by any means but they help to paint a picture of the current and future energy status of the world. This outlook is reasonable, though the predictions are certainly not completely objective as they are from an energy company themselves.

2.4 Economics

Table 1: Average Retail Price of Electricity to Ultimate Customers (cents/kWh) (6)

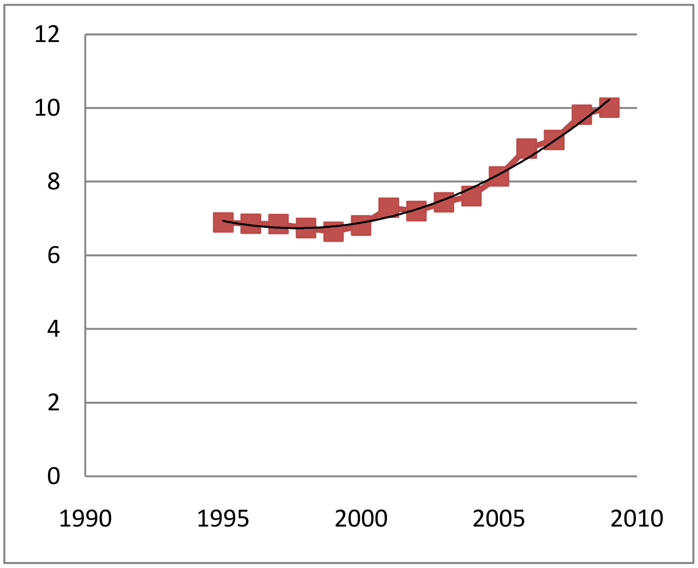


Period	Residential	Commercial	Industrial	Transportation	Other	All Sectors
Total Electric Industry[1]						
1997	8.43	7.59	4.53	NA	6.91	6.85
1998	8.26	7.41	4.48	NA	6.63	6.74
1999	8.16	7.26	4.43	NA	6.35	6.64
2000	8.24	7.43	4.64	NA	6.56	6.81
2001	8.58	7.92	5.05	NA	7.20	7.29
2002	8.44	7.89	4.88	NA	6.75	7.20
2003	8.72	8.03	5.11	7.54	NA	7.44
2004	8.95	8.17	5.25	7.18	NA	7.61
2005	9.45	8.67	5.73	8.57	NA	8.14
2006	10.40	9.46	6.16	9.54	NA	8.90
2007	10.65	9.65	6.39	9.70	NA	9.13
2008	11.26	10.36	6.83	10.74	NA	9.74

Table 2: Average Retail Electricity Price for all Sectors (cents/kWh) (2)

Year	Electricity Price (cents per KWh)
1995	6.89
1996	6.86
1997	6.85
1998	6.74
1999	6.64
2000	6.81
2001	7.29
2002	7.20
2003	7.44
2004	7.61
2005	8.14
2006	8.90
2007	9.13
2008	9.82
2009	10.01

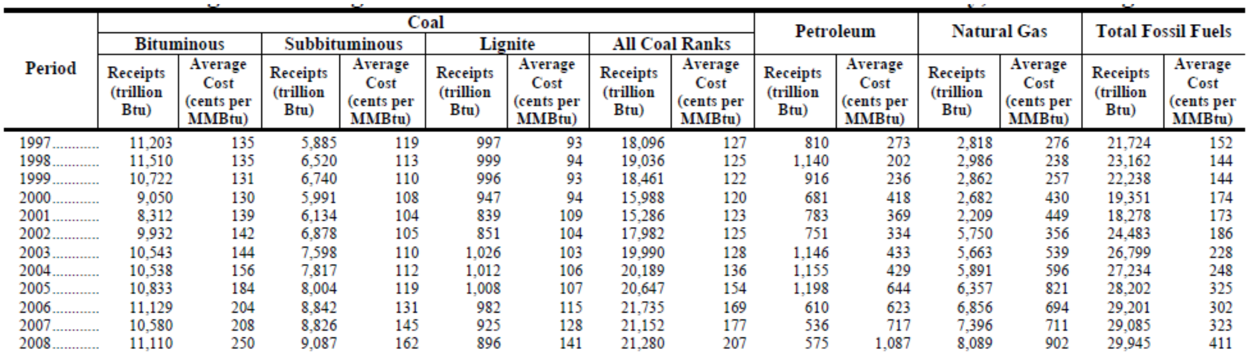
Figure 12: Electricity Prices, 1995-2009 (2)



All Sectors: Residential, Commercial, Industrial, Transportation

From the graph above, one can see that the retail price of electricity has risen steadily over the past 10 years. This rise in the price of electricity has coincided with rising fossil fuel costs for power generation, as shown in the chart below.

Table 3: Weighted Average Cost of Fossil Fuels to the Electric Power Industry (15)



Period	Coal								Petroleum		Natural Gas		Total Fossil Fuels	
	Bituminous		Subbituminous		Lignite		All Coal Ranks							
	Receipts (trillion Btu)	Average Cost (cents per MMBtu)	Receipts (trillion Btu)	Average Cost (cents per MMBtu)	Receipts (trillion Btu)	Average Cost (cents per MMBtu)	Receipts (trillion Btu)	Average Cost (cents per MMBtu)	Receipts (trillion Btu)	Average Cost (cents per MMBtu)	Receipts (trillion Btu)	Average Cost (cents per MMBtu)	Receipts (trillion Btu)	Average Cost (cents per MMBtu)
1997	11,203	135	5,885	119	997	93	18,096	127	810	273	2,818	276	21,724	152
1998	11,510	135	6,520	113	999	94	19,036	125	1,140	202	2,986	238	23,162	144
1999	10,722	131	6,740	110	996	93	18,461	122	916	236	2,862	257	22,238	144
2000	9,050	130	5,991	108	947	94	15,988	120	681	418	2,682	430	19,351	174
2001	8,312	139	6,134	104	839	109	15,286	123	783	369	2,209	449	18,278	173
2002	9,932	142	6,878	105	851	104	17,982	125	751	334	5,750	356	24,483	186
2003	10,543	144	7,598	110	1,026	103	19,990	128	1,146	433	5,663	539	26,799	228
2004	10,538	156	7,817	112	1,012	106	20,189	136	1,155	429	5,891	596	27,234	248
2005	10,833	184	8,004	119	1,008	107	20,647	154	1,198	644	6,357	821	28,202	325
2006	11,129	204	8,842	131	982	115	21,735	169	610	623	6,856	694	29,201	302
2007	10,580	208	8,826	145	925	128	21,152	177	536	717	7,396	711	29,085	323
2008	11,110	250	9,087	162	896	141	21,280	207	575	1,087	8,089	902	29,945	411

The previous chart shows only the cost of fuel for the power providers. These prices are not the end prices paid by the consumer. These prices do show that the fuel costs for coal generation are much less than that of petroleum and natural gas. One reason why there is a great push for renewable energy generation is that the “fuel” is typically abundant and free.

Table 4: Fuel Costs for the Electric Power Industry (cents/kWh) (15)

	Coal (All Ranks)		Petroleum		Natural Gas	
	Cents per MMBTu	Cents per KWh	Cents per MMBTu	Cents per KWh	Cents per MMBTu	Cents per KWh
2006	169	0.58	623	2.1	694	2.4
2007	177	0.60	717	2.5	711	2.4
2008	207	0.71	1,087	3.7	902	3.1

1 KWh = 0.003413 MMBTu

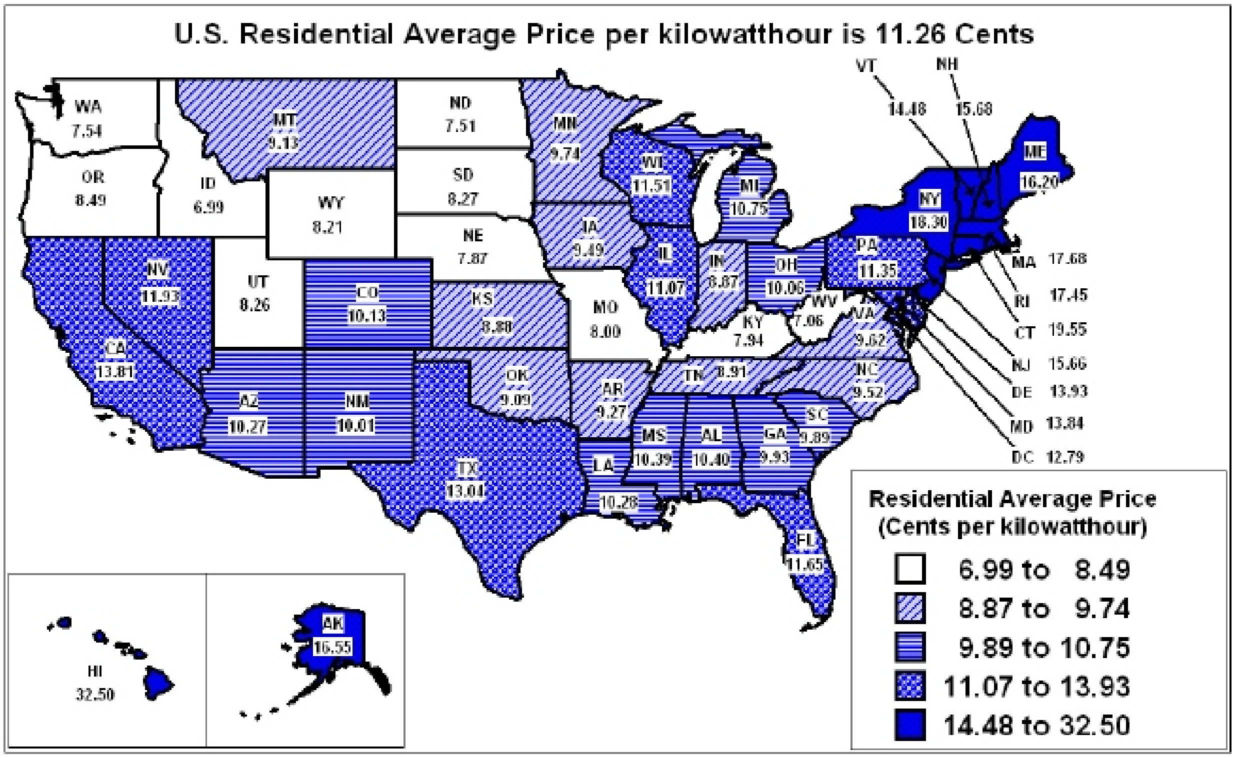
There are many factors that go into the end price paid by the consumer for power, as shown below in the chart from the EIA. All of these factors need to be considered when determining the cost of delivered power.

Table 5: US Prices by Service Category (2008 cents/kWh) (19)

Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Generation	6.2	6.7	6.5	5.9	5.4	5.7
Transmission	0.7	0.7	0.7	0.8	0.8	0.8
Distribution	2.4	2.4	2.4	2.5	2.4	2.5

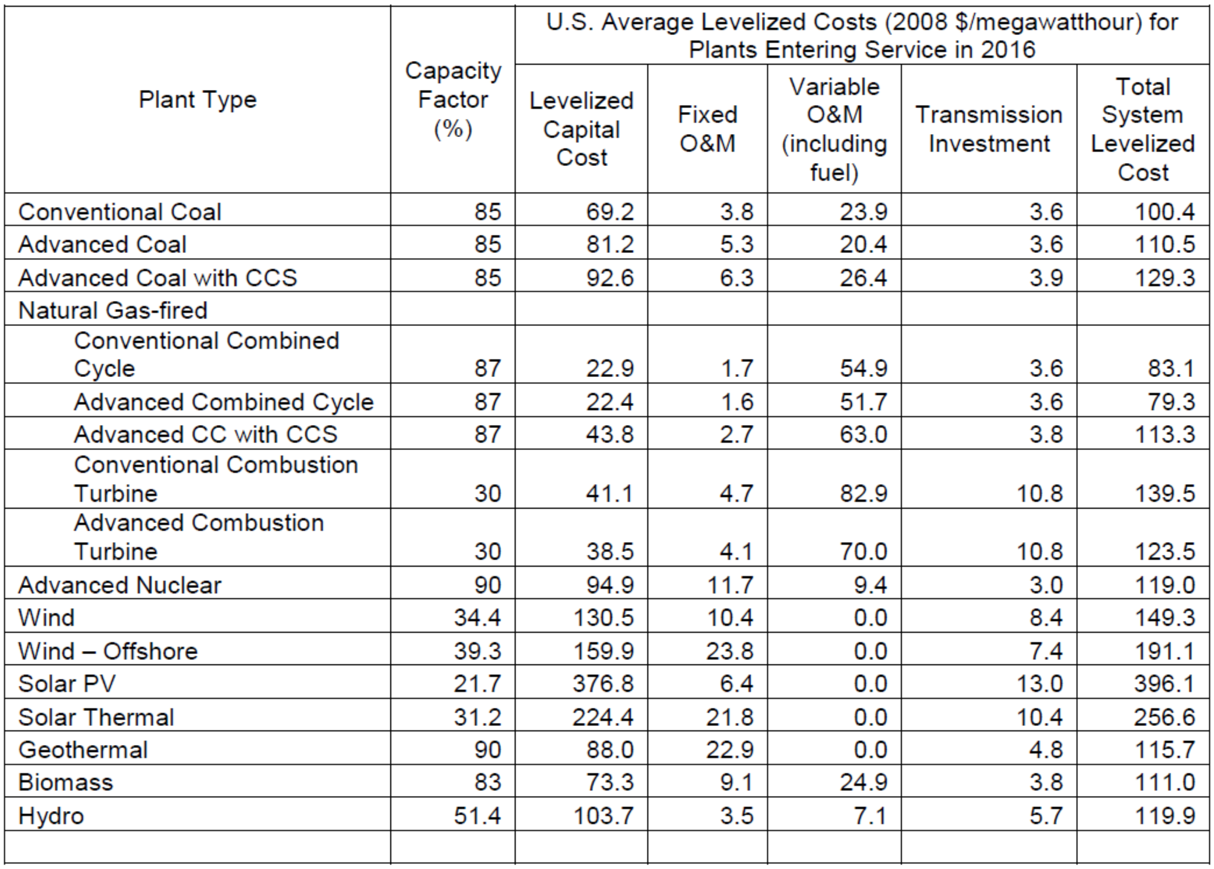
The largest component of the cost of electricity is in the generation, which has several components itself. The cost of fuel is an important factor, with coal being much less than natural gas as was shown earlier. The cost of constructing the plant is also important, as construction and maintenance costs are greater for some kinds of power plants than others. Maintaining and using the transmission system to deliver electricity is also a large component of the cost of electricity. In some states, prices are fully regulated by Public Service Commissions, while in others there is a combination of unregulated prices (for generators) and regulated prices (for transmission and distribution). Energy prices vary across the U.S. in different states and during different times of the year. Even something as temporary as weather conditions can affect the price of electricity (1). The following chart shows the relatively large variation in the average residential price of electricity in each state.

Figure 13: Average Residential Price of Electricity by State, 2008 (6)



The following costs are an estimate by the EIA for the average levelized cost of new energy generation resources for the year 2016. These predictions involved many assumptions based on the available data. The chart is best used as a template for the compared costs of electricity generated from various sources.

Table 6: Estimated Levelized Cost of New Generation Resources, 2016 (17)



Plant Type	Capacity Factor (%)	U.S. Average Levelized Costs (2008 $/megawatthour) for Plants Entering Service in 2016				
		Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Transmission Investment	Total System Levelized Cost
Conventional Coal	85	69.2	3.8	23.9	3.6	100.4
Advanced Coal	85	81.2	5.3	20.4	3.6	110.5
Advanced Coal with CCS	85	92.6	6.3	26.4	3.9	129.3
Natural Gas-fired						
Conventional Combined Cycle	87	22.9	1.7	54.9	3.6	83.1
Advanced Combined Cycle	87	22.4	1.6	51.7	3.6	79.3
Advanced CC with CCS	87	43.8	2.7	63.0	3.8	113.3
Conventional Combustion Turbine	30	41.1	4.7	82.9	10.8	139.5
Advanced Combustion Turbine	30	38.5	4.1	70.0	10.8	123.5
Advanced Nuclear	90	94.9	11.7	9.4	3.0	119.0
Wind	34.4	130.5	10.4	0.0	8.4	149.3
Wind – Offshore	39.3	159.9	23.8	0.0	7.4	191.1
Solar PV	21.7	376.8	6.4	0.0	13.0	396.1
Solar Thermal	31.2	224.4	21.8	0.0	10.4	256.6
Geothermal	90	88.0	22.9	0.0	4.8	115.7
Biomass	83	73.3	9.1	24.9	3.8	111.0
Hydro	51.4	103.7	3.5	7.1	5.7	119.9

The levelized cost estimates show the fossil fuels still have the advantage of being generally the most affordable options for energy generation. Nevertheless, sources such as nuclear, wind, geothermal, biomass and hydro can effectively make affordable energy as shown and offer added benefits that fossil fuels don't such as tax breaks for renewable energy, taxes on carbon emissions as well as the benefit of protecting the environment from pollution. Determining the costs of electricity from renewable sources can be complex because most of the costs for renewable plants occur up front in the design and building stages. In order to determine the price per kilowatt hour that is being paid, difficult assumptions need to be made on the lifetime and capacity factor of the plant. A further and more in-depth analysis on the true costs of wind energy will be discussed in later sections.

2.5 Present and Future State of Electricity Production

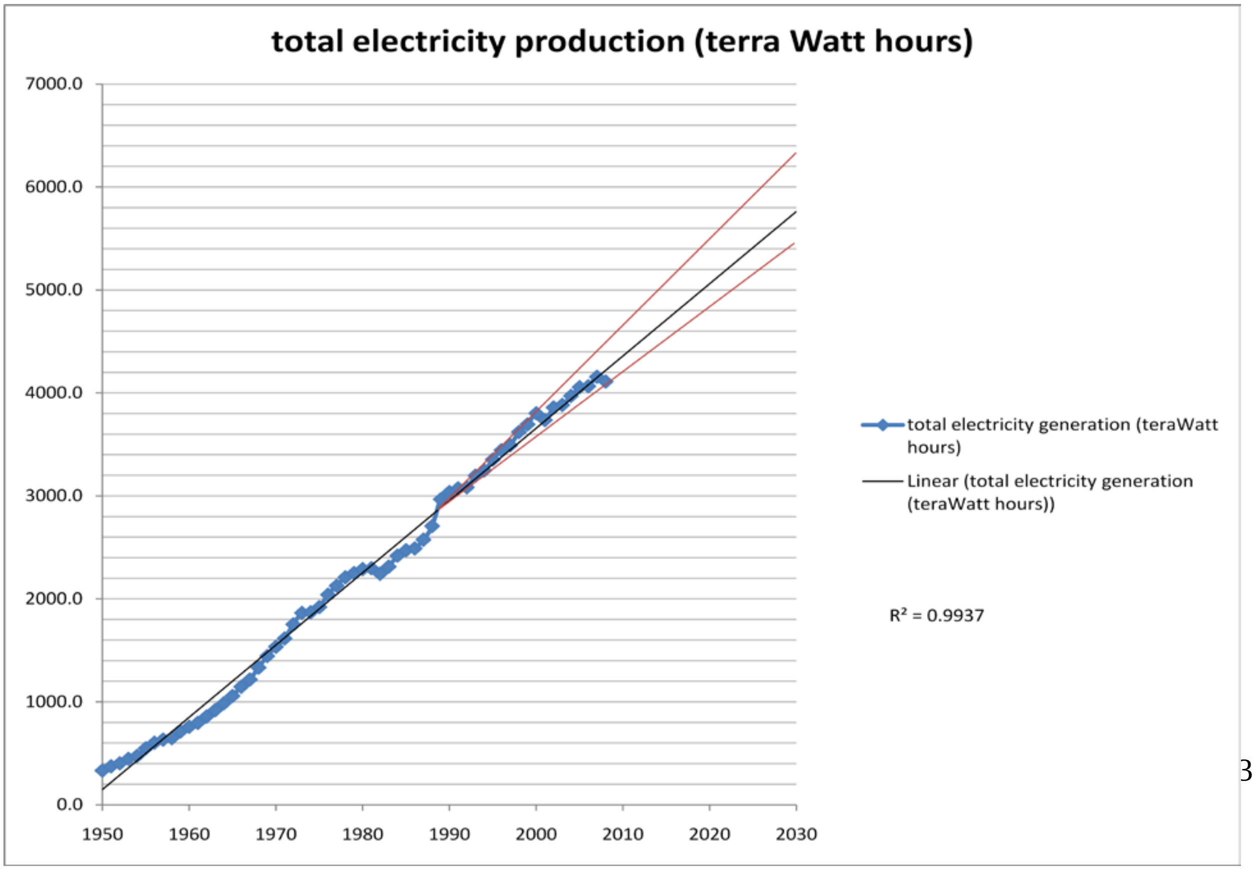
2.5.1 Model components

The goal of this section is to predict the future role of different energy sources in the production of electricity. From these estimates, conclusions will be drawn as to the potential growth of wind generated electricity in the near future. Historical production data from the major sources of electricity generation is used to generate plots which are then fitted with least squares trend lines. The trend lines are then extrapolated forward in time to estimate likely future electrical generation from that source. The current main sources of coal, natural gas, nuclear, hydro, and wind are considered for prediction purposes, while other minor energy sources are not included as their growth rate is negligible, or their overall contribution is negligible. The period from 2008 through 2030 was used to give a 22 year extrapolation. The choice of 2030 is somewhat arbitrary, but results in the prediction period not being greater than 1/3 of the actual data history for most of the energy sources considered. Also, 2030 coincides with the target year for a major DOE sponsored study on wind power growth, with the goal of achieving 20% of our electricity from wind generation by 2030. Since the predictions made from the modeling done in this report will also be used to evaluate the feasibility of future wind generation, 2030 seems an appropriate target year.

2.5.2 Total Electricity Production

This quantity is used in the model as production is directly correlated and very close in value to demand for electricity, so the extrapolation should also reflect future demand. A linear trend line was used resulting in a very good fit for the entire data history since 1950. By extrapolating the trend line, the predicted value for 2030 was approximately 5800 terawatt hours of electricity generation. The more distinct trend starting in the late 1980's was then used to estimate an error range for the prediction. Lines were drawn through the highest and lowest data points of this section. Since this section of the data was also nearly perfectly linear, the error was small, giving a range between 5400 and 6400 terawatt hours. Compared to the 2008 value, the mean estimate for 2030 of 5800 TWh represents a growth of about 41%, while the low and high estimates give growths of 31% and 56% respectively. Averaged over each year between 2008 and 2030, a total growth of 41% would represent approximately 77 TWh in new electricity production being added to the grid each year.

Figure 14: US Total Electricity Production (TWh)

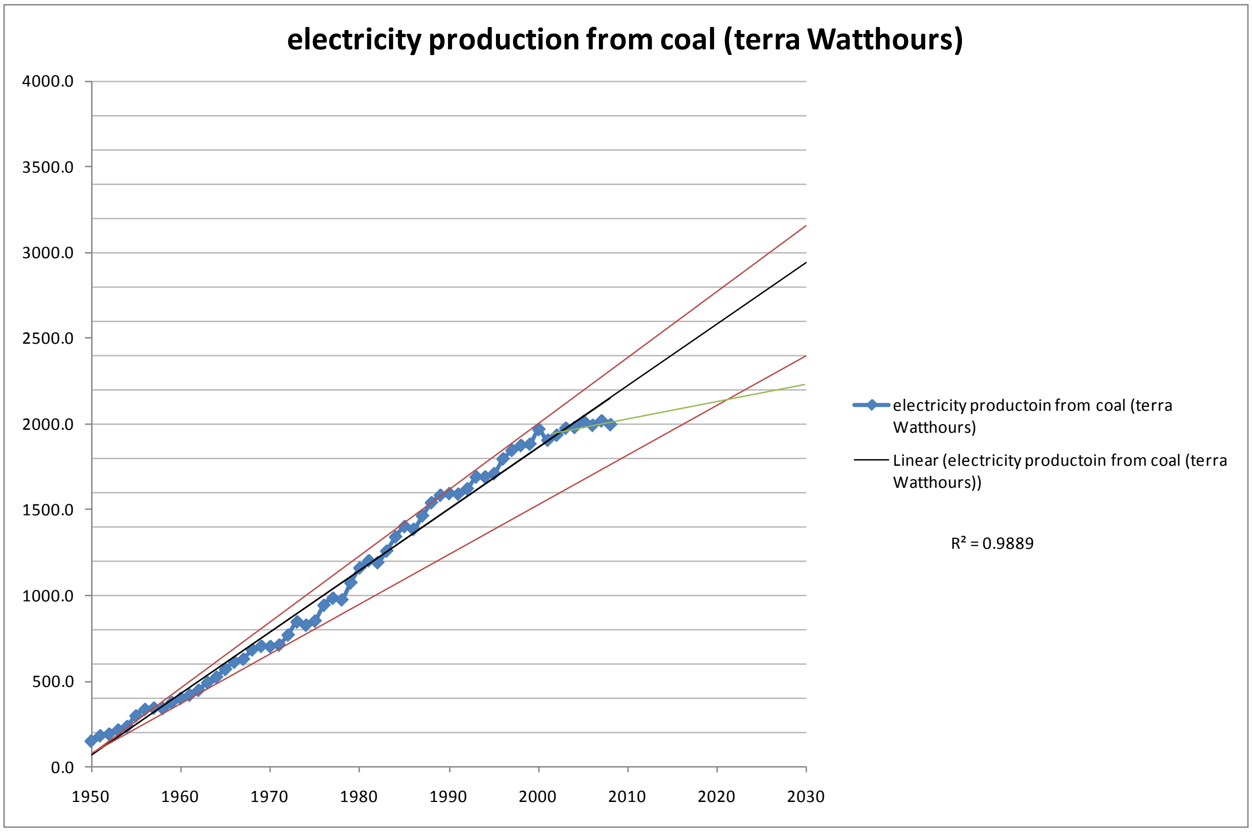


2.5.3 Electricity Production from Coal

The historical production data for electricity generated from coal-fired power plants dates back to 1950, just like total electricity production data. The overall trend up through 2008 is quite linear in appearance and was fitted with a linear regression giving an R^2 value of .99. This line was then extrapolated to the target year of 2030 to give a mean production estimate of 3000 TWh. Lines were also fit to the high and low extreme data points in the series to give error estimates, resulting in predictions of 2400 and 3200 TWh. The mean estimate would represent a growth of approximately 48% between 2008 and 2030, while the low and high estimates represent growths of 20% and 60% respectively.

Upon closer examination of the graph, however, a new and distinct trend in the data can be seen starting around 2001. From this point up to the present, the growth is significantly slower compared to the earlier data. The extrapolation of the most recent data results in a much lower prediction of about 2200 TWh by the year 2030. This would represent a more likely scenario with a total electrical production growth of approximately 10%. Although the actual situation which will occur is dependent on many complex factors, there are a few major factors which can be considered here. The slower growth in electricity generated from coal since 2001 is a direct result of the fact that very few new coal fired power plants have come online in this time period. Coal fired plants are generally large in capacity compared to other electricity generation sources, so there are much greater capital or "upfront costs" in building new coal plants compared to smaller scale power plants. Another factor which would suggest a greater increase in coal generated electricity is the large domestic reserves of coal in the US, giving it an advantage over fuels which are being increasingly imported. A brief look at recent electric power generation additions should give some insight to coals' future role, though. Of the 21 GW of new generating capacity that was planned for 2008, only 1.1 GW was from coal fired plants, while natural gas and wind made up 19.6 GW combined. This is quite surprising considering that coal was responsible for nearly 49% of all electricity production in 2008.

Figure 15: US Electricity Production from Coal (TWh)



2.5.4 Electricity Production from Natural Gas

The historical data for electricity generated from natural gas contains a fair amount of "noise" or frequent variations. Because of this, it is difficult to fit one trend line for the entire data series. A quadratic regression curve does give the best fit for the entire data, but overall still isn't a good representation. There are three different distinct trends present in the data since

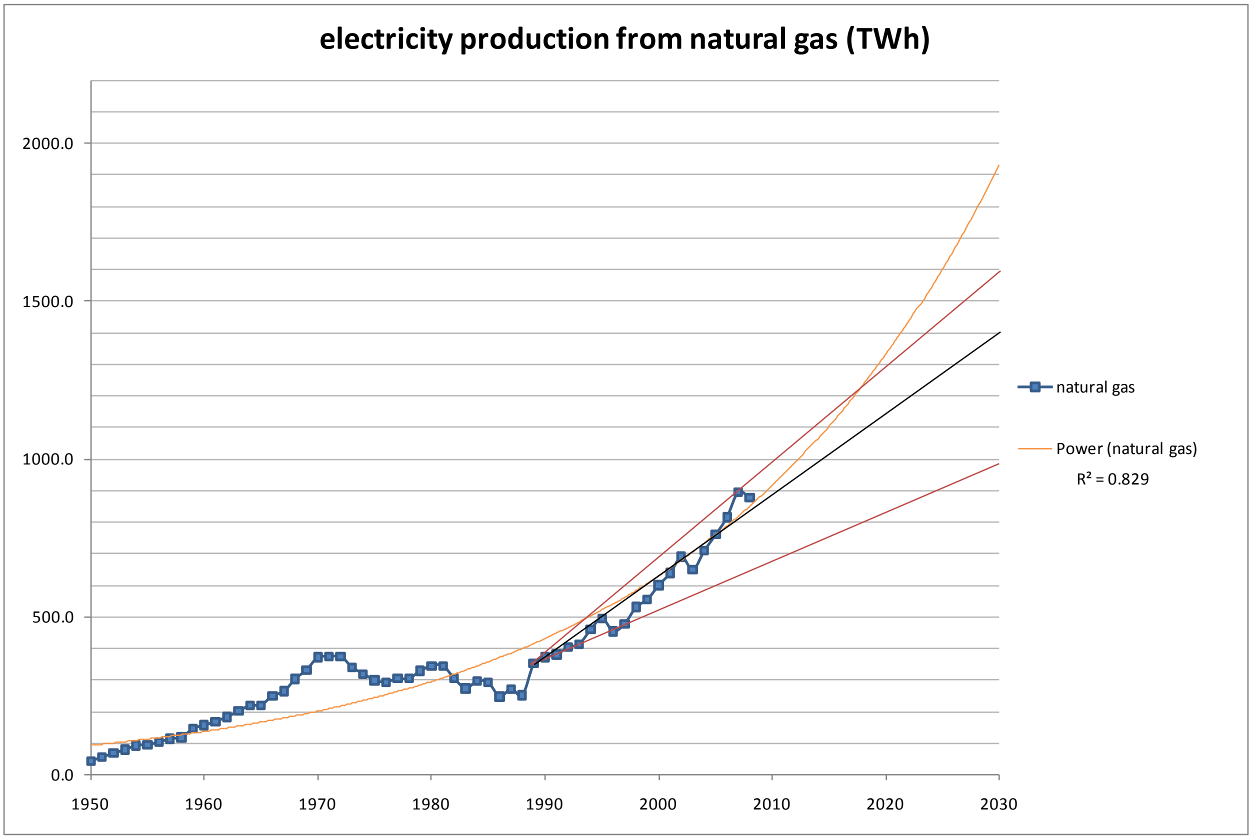
1950. In the period between 1950 and 1970, production from natural gas increased steadily almost every year and then plateaued for about three years in the early 1970’s. From this point until the late 1980’s, production varied up and down with a net decline of about 100 TWh. Since approximately 1990 however, production has experienced a sharp increase up to the present, with a total growth of about 500 TWh, which is nearly a 120% increase. In order to make meaningful predictions, only this most recent data trend was used for extrapolation into the future. This resulted in a mean prediction of 1400 TWh by 2030, with low and high estimates of 1000 and 1600 TWh respectively. The mean prediction gives a growth of about 55% over the present value, while the low and high estimates result in growths of approximately 11% and 78%.

When examining the recent growth in natural gas usage for electricity production, there is an odd correlation with price. While natural gas prices remained relatively flat for a long period prior to 2000, prices have climbed at a significant rate from 2000 to present. As was discussed though, usage of natural gas for electricity production has experienced its fastest growth also in this most recent period from 2000 on. The natural assumption would be that production would slowdown in growth as prices rise, but this is not what has happened in reality. Despite natural gas having the highest cost per quantity of electricity generated out of all other non renewable energy sources, the majority of new electricity production from non renewable sources in the last decade has come from natural gas generation. One answer to this paradox is in how costs are distributed.

Natural gas is unique in its cost structure, as a majority of the cost in generating electricity is from the fuel cost itself. The other major electric generation sources of coal and nuclear both have lower fuel costs than natural gas, however the difference is in their upfront costs. Upfront costs are the investments that must be made in order to get an electric power plant up and operational. Both nuclear and coal plants are typically built for large production capacities, and as a result, the upfront cost of adding any new capacity is also very large. By contrast, natural gas generation plants can be built in many different capacities, depending on the current demand. The reality is that electricity demand increases in what is essentially a continuous rate, so when deciding how to meet new demand, the decision recently has been to make small, incremental additions rather than fewer larger additions to production. Natural gas technology is able to be used economically in this way by adding, or in some cases bringing online, the required number of small units only when they are needed. Nuclear and coal based generation methods are not able to provide new capacity in this small, incremental manner, as they are only economically feasible when operated continuously on a large scale.

Essentially, the recent trend in new electrical generation capacity has reflected a preference for low initial cost technologies, despite the fact that in the long term, they are more expensive than large scale nuclear or coal plants.

Figure 16: US Electricity Production from Natural Gas (TWh)



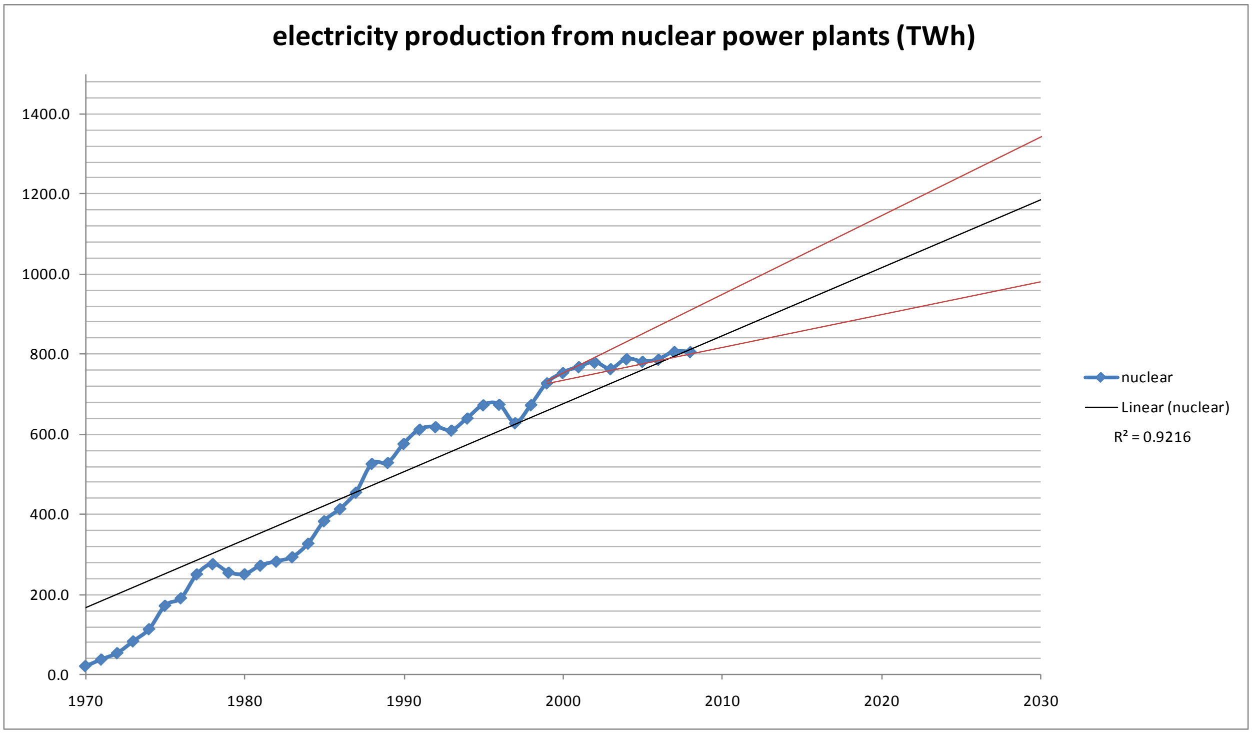
2.5.5 Electricity Production from Nuclear Power

The production history from nuclear power began more recently starting in 1970 with less than 40 TWh initially. The observed growth in nuclear power has experienced many different individual trends over its entire history, but was fit with a linear regression line giving an acceptable R^2 value of .92. However, growth was much more significant in the earlier periods up to around 1990. From this point forward, the data better matches the overall linear trend line. This analysis gives a mean prediction for 2030 of approximately 1200 TWh, a growth of about 50%. However, the most recent data since 2000 displays a different trend representing a slower growth rate in production. In order to make more realistic predictions, only this most recent data since 2000 was used to establish high and low value predictions, yielding 1350 and

1000 TWh respectively. These values give growths of about 69% and 25%. The more likely scenario for growth would be the lower estimate when the matter is examined more closely.

Since 1990, there have been no new nuclear power plants constructed, and in fact the number of operable plants has actually decreased from a peak of 112 to the current value of 104. This raises the question of how production has managed to increase at all over the last two decades. This has been accomplished through the modification and upgrading of existing plants. Unfortunately though, this practice has its limits, as a plant physically can only be modified so much without requiring entirely new supporting systems. Looking into the future, there are no current plans to add new nuclear generating capacity through 2011. As it stands right now, it seems unlikely that there will be significant growth in nuclear power in the near future. However, even with no growth, the current production of about 800 TWh will constitute a significant portion of electric production for some time to come.

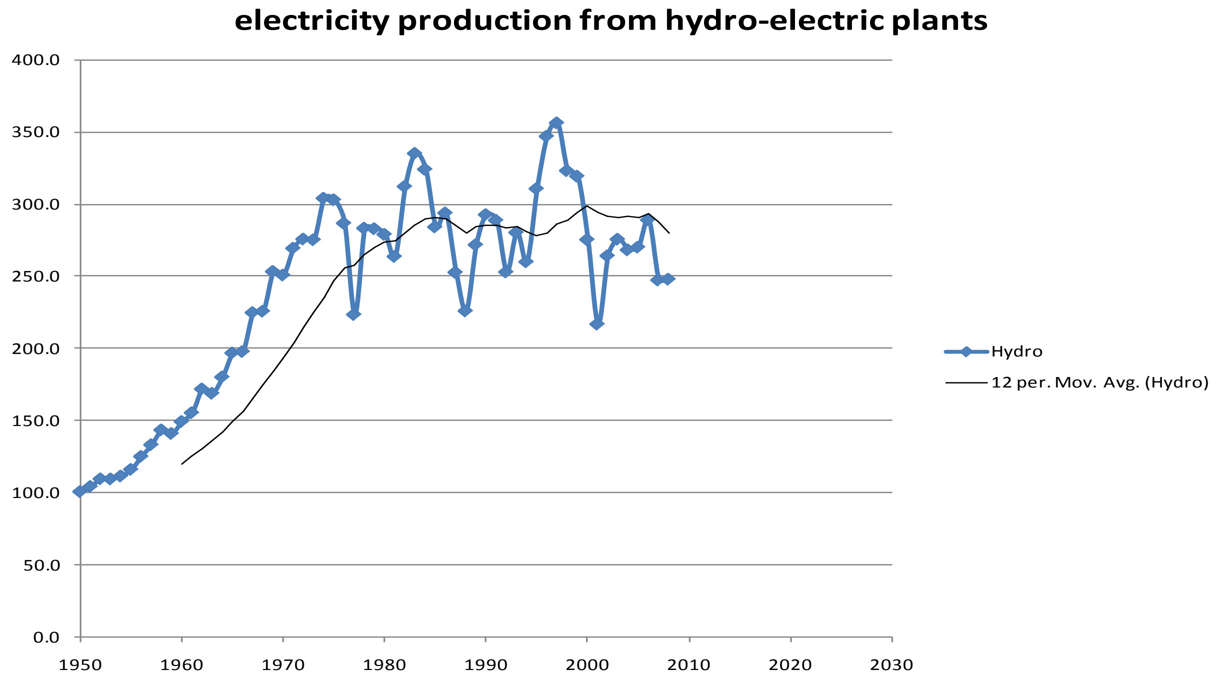
<u>Figure 17: US Electricity Production from Nuclear Power Plants (TWh)</u>



2.5.6 Electricity Production from Hydropower

Since 1950 hydroelectric power has been America's largest source of renewable electricity. Initial growth was quite fast up to the mid 1970's, at which point it produced nearly 20% of all electricity. From this point up to the present, though, production has been very erratic, declining and then rising again on nearly an annual basis. For this reason, it is nearly impossible to reliably predict any net growth in the future for hydropower. There are a few main factors influencing this lack of a trend. For one, the hydropower infrastructure in the US is quite mature, as almost all of the best sites already have units operating. Secondly, the advent of stricter environmental regulations has blocked the construction of new major projects. Finally, the ultimate fuel source for hydro power, rainwater, also varies greatly from year to year. So when the generating capacity remains fairly constant, the influence of change in water availability becomes much more apparent. For these reasons, it is assumed that on average, hydropower production remains fairly constant in the future.

Figure 18: US Electricity Production from Hydro-Electric Plants (TWh)



2.5.7 Electricity Production from Wind Power

Wind power is the current wild card in electricity production. Its current production is only about 1% of total electric production, but it has experienced extremely high growth rates since 2000. Using data starting from 1990, exponential regression curves were fit to the entire data series, and also to just the most recent data since 2000. The overall exponential regression predicts a production value of 750 TWh by 2030 with an R^2 value of .87. Using the more recent data since 2000, an exponential trend line predicts production to be well over 1000 TWh before 2020. Although the fit is much closer using only the most recent data, giving an R^2 value of .98, the growth required to achieve this extremely unlikely. Using the early history of other energy sources, a more likely growth scenario for wind is a continuation of exponential growth followed by decay to slower growth rates. This general trend reflects a logistic curve's properties. In order to give more likely estimates of future wind production, two logistic shaped curves were created that initially closely follow the two exponential curves. Using this method, the lower estimate is assumed to begin declining in growth around 2020 and yields a value of about 500 TWh by 2030. The higher initial growth rate curve is assumed to begin declining around 2017 and yields a value of approximately 1100 TWh by 2030. This later value would be sufficient to meet the goal of 20% wind generation by 2030.

Figure 19: US Electricity Generated from Wind Turbines (TWh)

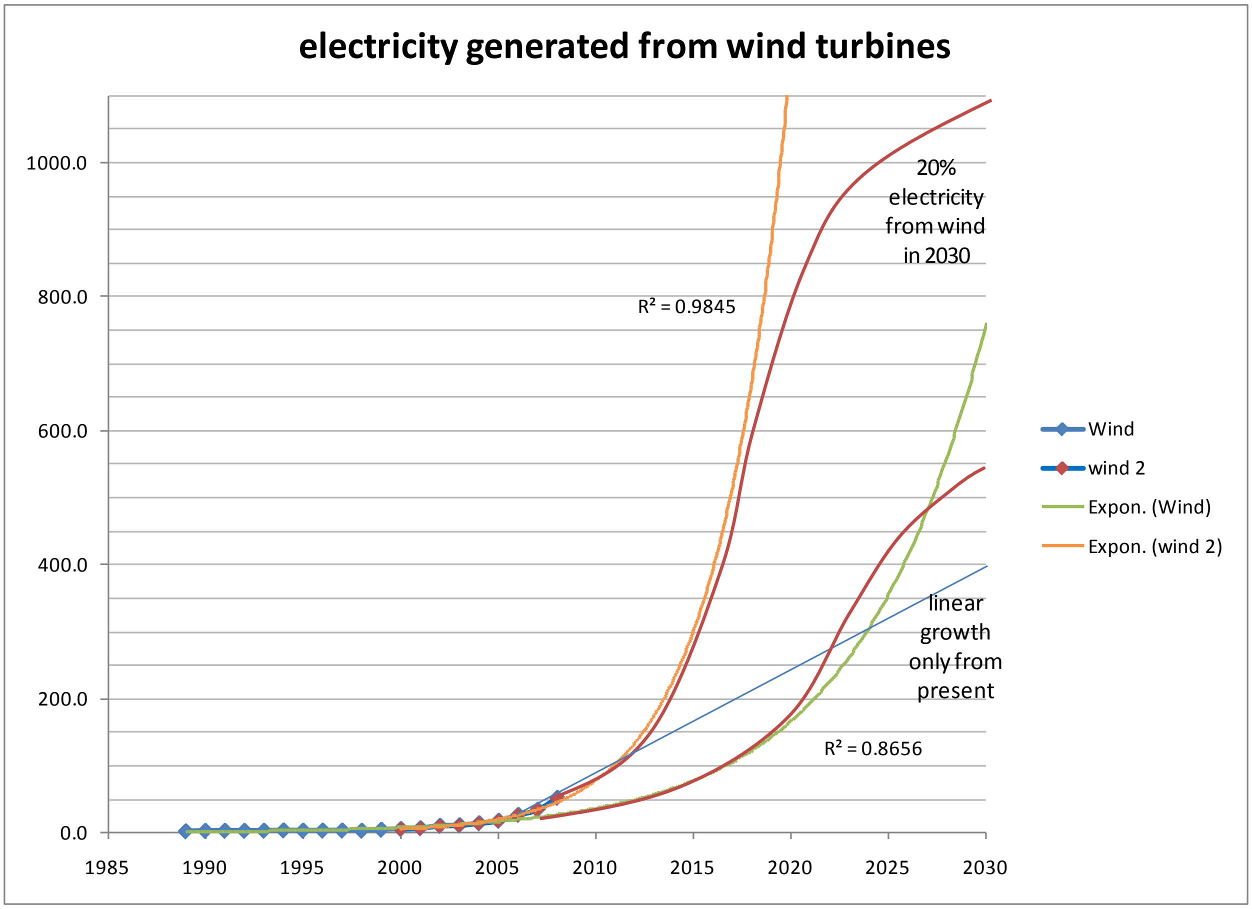


Table 7: Total Electricity Production Estimates

Totals

2030	total electricity	coal	natural gas	nuclear	hydro	wind	prediction sum	fraction
low estimate	5400.0	2400	1000	1000	240	350	4990	0.92
mean prediction	5800.0	3000	1400	1200	280	500	6380	1.10
high estimate	6400.0	3200	1600	1350	360	1100	7610	1.19
Adjusted values								
low estimate		2597	1082	1082	260	379	5400	
mean prediction		2727	1273	1091	255	455	5800	
high estimate		2691	1346	1135	303	925	6400	

The adjusted values are simply proportionally scaled prediction values. This was done so that the total sum of all sources for each estimate type was equal to the total electricity production estimate. The sum of predictions from the low estimate is less than the total electric production, while the mean and high estimates are both greater.

2.6 Resource Availability

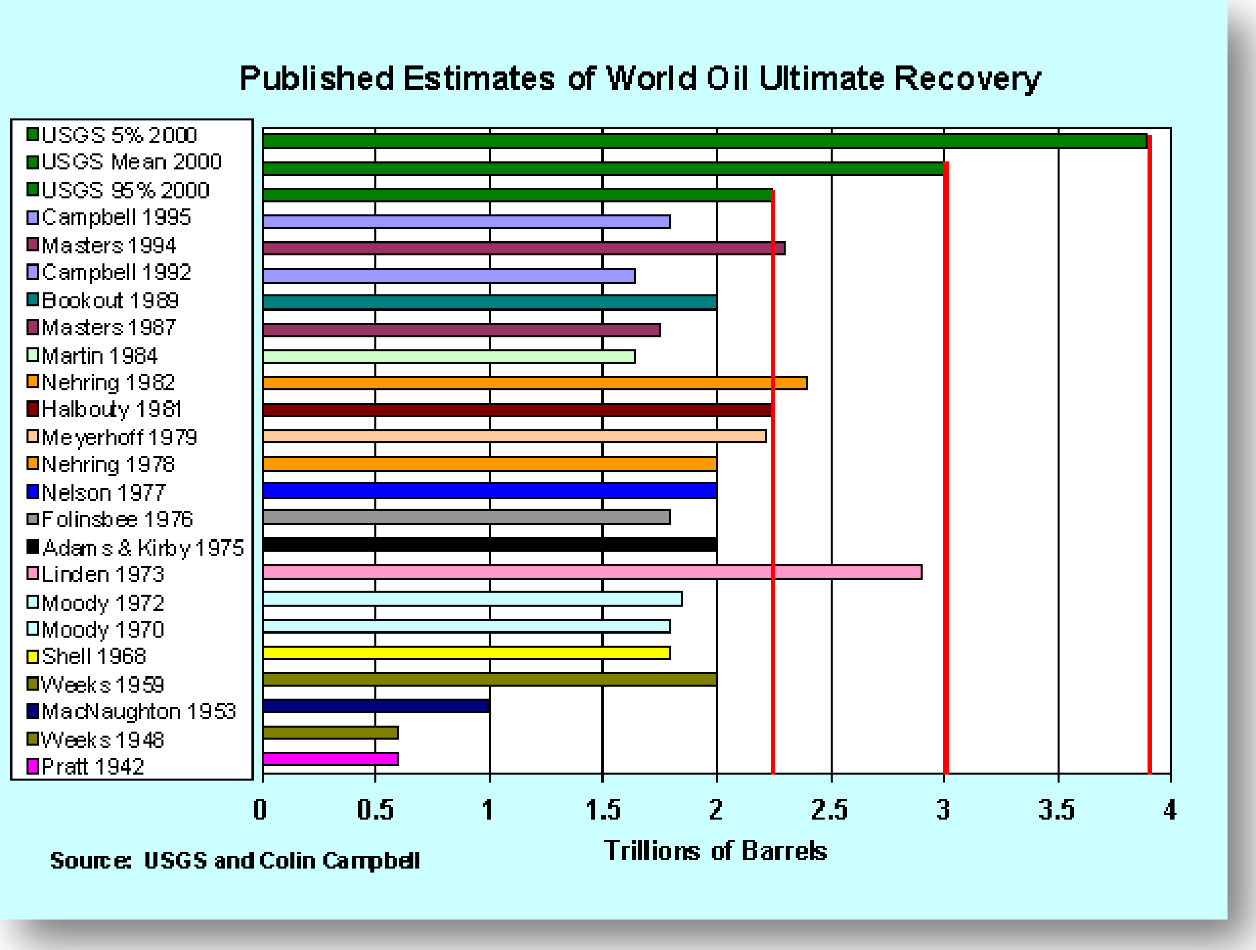
2.6.1 The Future of the Oil Supply

Predicting anything in the future is no simple task to say the least. Even the weather in two days from now is uncertain. When the timescale is in years and decades, most predictions become extremely complex, and assumptions must be made if any meaningful result is to be reached. This is exactly true in the case of the world oil supply.

When trying to answer the question of how much oil is actually remaining in the world, and how long it will last us, there are both many different measurements we can consider and many different assumptions we can make. The broadest measurement of world oil supply is what is known as initially in place oil. Estimates of this quantity attempt to represent the total amount of oil that was present within the Earth when production first began. This figure represents the ultimate physical limit of the resource, but is not practical in measuring how much oil we can produce. Due to this and the shear difficulty in accounting for all the oil around the globe, there are not many well established estimates of this quantity.

A more useful measurement of the world oil supply is what is referred to as world oil ultimate recovery. This measures the amount of oil that is technically feasible to be recovered or produced, and includes both current cumulative production, and all likely future production. As such, there must be some assumptions made regarding improvements in future recovery and exploration technologies. Also, the amount that will be recovered is highly dependent on future prices, as some sources are more expensive to produce oil from, and would only be viable if prices were high enough to make it profitable. Following is a chart with the history of major estimates of ultimate recoverable oil.

Figure 20: Published Estimates of World Oil Ultimate Recovery (20)

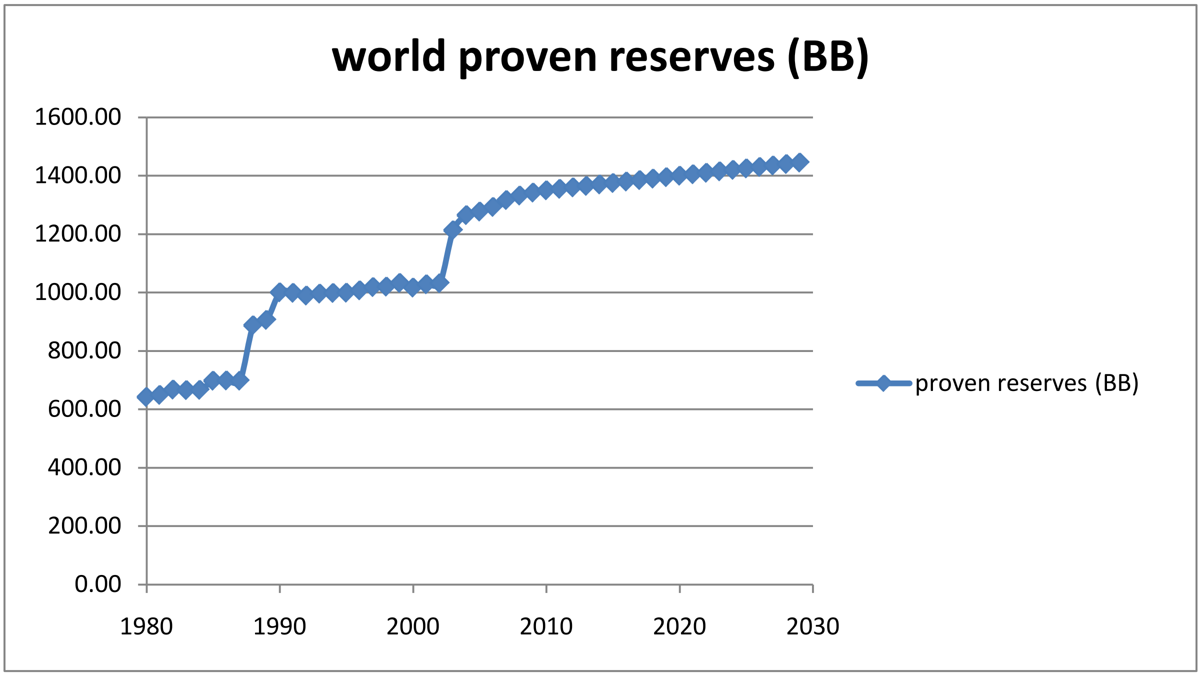


The most recent estimates performed by the US Geological Survey in 2000 are given in three different values. These represent different statistical likelihoods. The value listed as mean represents the quantity at which there is an equal probability of the actual value being higher or lower, and therefore is most reliable when modeling the oil supply. The 5% and 95% estimates represent the values at which their respective probabilities (.05 and .95) are the chances that the actual amount of ultimate recoverable oil is greater than the estimate value.

As can be seen, there is a slight upward trend in these estimates over time, reflecting the technological improvements made in the surveying process. The most recent value of ultimate recoverable oil from the USGS mean of 3 trillion barrels will be used for modeling and prediction purposes. By definition, this value can further be broken down into two parts. The first part is the value of cumulative oil production to date, which is known from records. At the end of 2008, this value was approximately 840 Billion barrels (1). Subtracting this from the ultimate recoverable estimate gives 2,160 billion barrels, which represents the amount of oil that can likely be produced in the future. To further break things down, another important quantity which makes up a part of the remaining 2,160 billion barrels is referred to as proven reserves. Proven reserves are documented sources of oil for which there is a very high confidence in the ability to recover oil from them. In 2008, world proven reserves totaled about 1,340 billion barrels (1). However, the source of proven reserves data should be noted carefully. Although the EIA develops and composites these estimates from raw data, it can’t certify the validity of the original data, as it comes from a multitude of international sources. It should be noted that there is a level of skepticism particularly regarding data from OPEC member nations. It is believed by some that the proven reserve data from some of these nations is inflated beyond the true value. The basis for such accusations has relied mainly on the observation of increases in reported proven reserves from these nations, while at the same time, very little in the way of new oil discoveries have been made in these areas.

There is also a tendency for global proven reserve estimates to dramatically increase over very short periods of time. This pattern can be seen in a plot of world proven reserves over time, which was derived from EIA data.

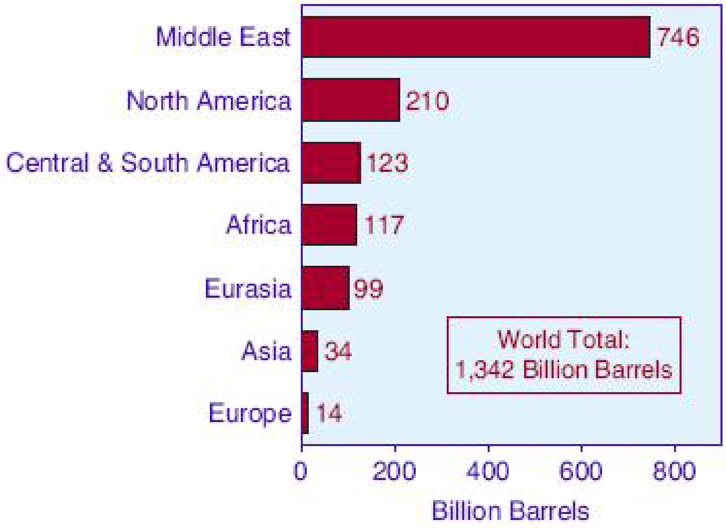
Figure 21: World Proven Oil Reserves



During both the late 1980's and early 2000's, the estimates rose suddenly, breaking with the long term trend, and then quickly returned to slower steady growth. In addition to the accusations of inflated estimates from some OPEC nations, there are two other possible explanations for these sudden increases. Rapid technological innovations in the oil discovery industry can certainly lead to new findings in existing oil fields that simply couldn't be located with older methods. Also, when reviews of past reserve data are conducted from time to time, more accurate modeling methods may yield larger quantities of oil. The result of this is a sudden revision to the reserves within a particular field or area.

The distribution of world proven reserves is not uniform across the globe, but rather concentrated in a few areas. At nearly 750 BB, the Middle East contains over half of all proven reserves in the world, an amount over 6 times greater than the average of other major oil producing areas.

Figure 22: World Proven Oil Reserves by Region, 2008 (21)

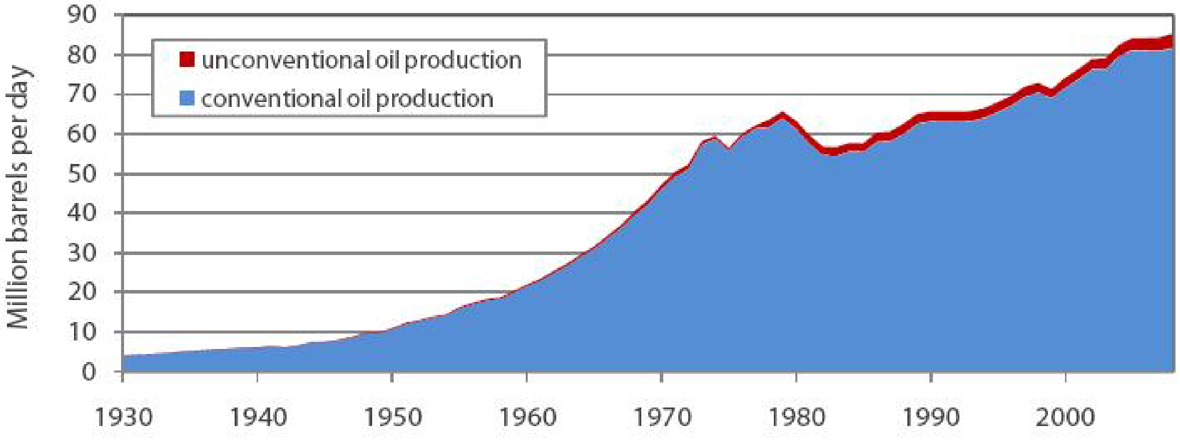


Source: "Worldwide Look at Reserves and Production," *Oil & Gas Journal*, Vol. 106, No. 48 (December 22, 2008), pp. 23-24.

2.6.2 Modeling the Remaining Oil Supply

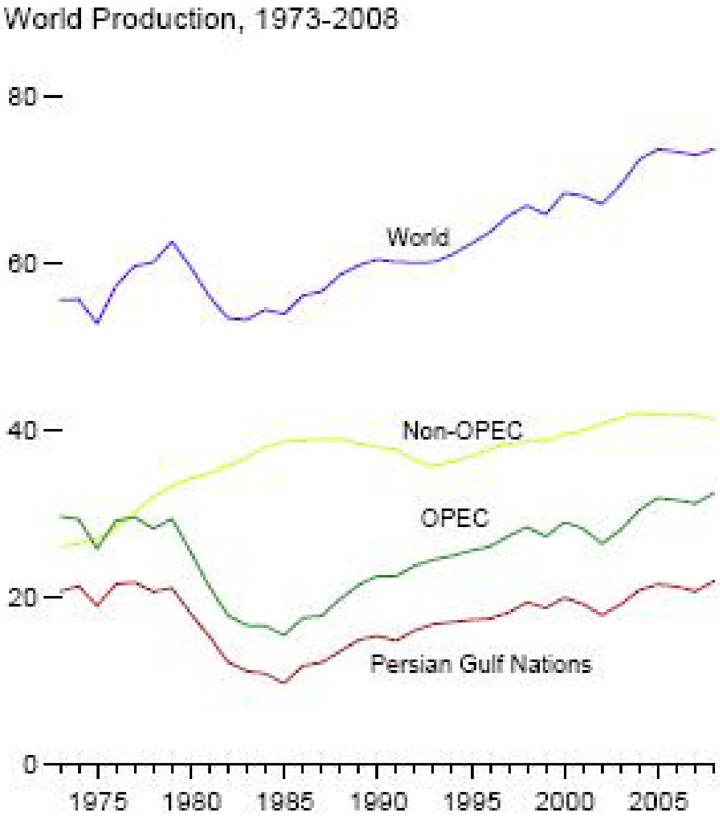
In an attempt to estimate how long the world oil supply will last, a simple model was constructed using historical data. As previously mentioned, the model begins with the most recent USGS estimate of World ultimate recoverable oil, made in 2000. From this point the cumulative oil production to date was subtracted, leaving the current quantity of recoverable oil at 2,160 billion barrels. In order to determine the rate of depletion of oil, historical production data was used to predict future production rates. Examining a plot of world oil production over time reveals two major trends, as seen in the following chart. Until the mid 1970's, production grew exponentially. Following this was an approximately 10 year period in which the prevailing trend was disrupted by sudden drops in production, mainly caused by OPEC member nations. Starting in the early to mid 1980's, a new linear trend in production began, and has continued up to the present.

Figure 23: Conventional and Unconventional Oil Production (22)



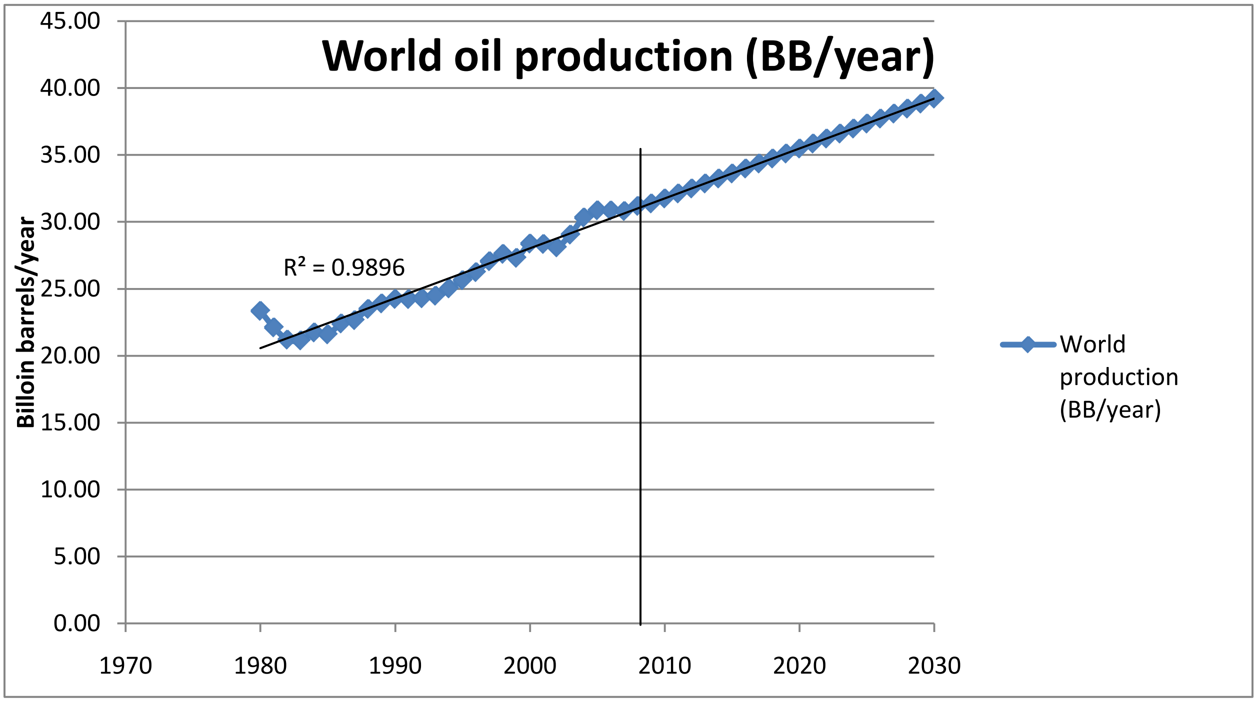
Data: IHS Energy, BP Statistical Review

Figure 24: World Oil Production, 1973-2008 (22)



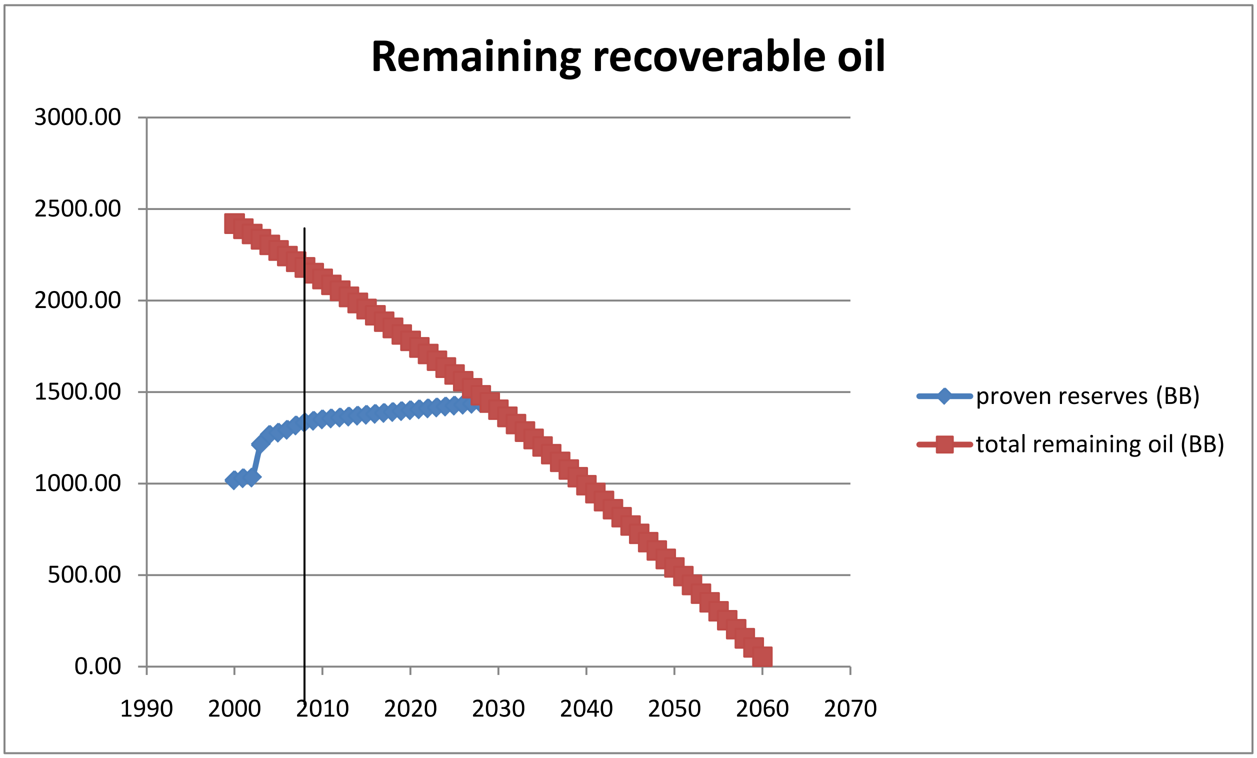
The more recent production data was analyzed and then extrapolated using a best fit line. As can be seen, the correlation value for the data is very high, suggesting that the trend is in fact very linear. Future production values were then determined from 2009 until 2030.

Figure 25: World Oil Production



In order to predict when the remaining oil supply would run out, the predicted future production values were cumulatively summed starting from the present year, and then subtracted from the current estimate of remaining recoverable oil. The results were plotted over time to determine when the amount of recoverable oil would be nearly zero.

Figure 26: World Remaining Recoverable Oil



Also included on this plot was the extrapolated data of proven reserves. An interesting feature occurs around the year 2030, when the quantity of proven reserves intersects the remaining oil supply. This event would represent the ultimate limit of reserves, as they can't be greater than the actual amount of remaining oil. At this point, reserves would then decline following the same curve as that of the total remaining oil. However, this situation is unlikely in reality, as it implies that we would be able to discover enough new reserves to both increase the total reserves and meet growing production right up until all oil is discovered, a practically impossible feat. A more likely scenario would see a decline in total reserves before this quantity intersects with the total remaining recoverable oil supply. Reserves would then continue to decline at a rate approaching that of the total remaining oil. Only when the total recoverable oil approached zero would reserves actually intersect.

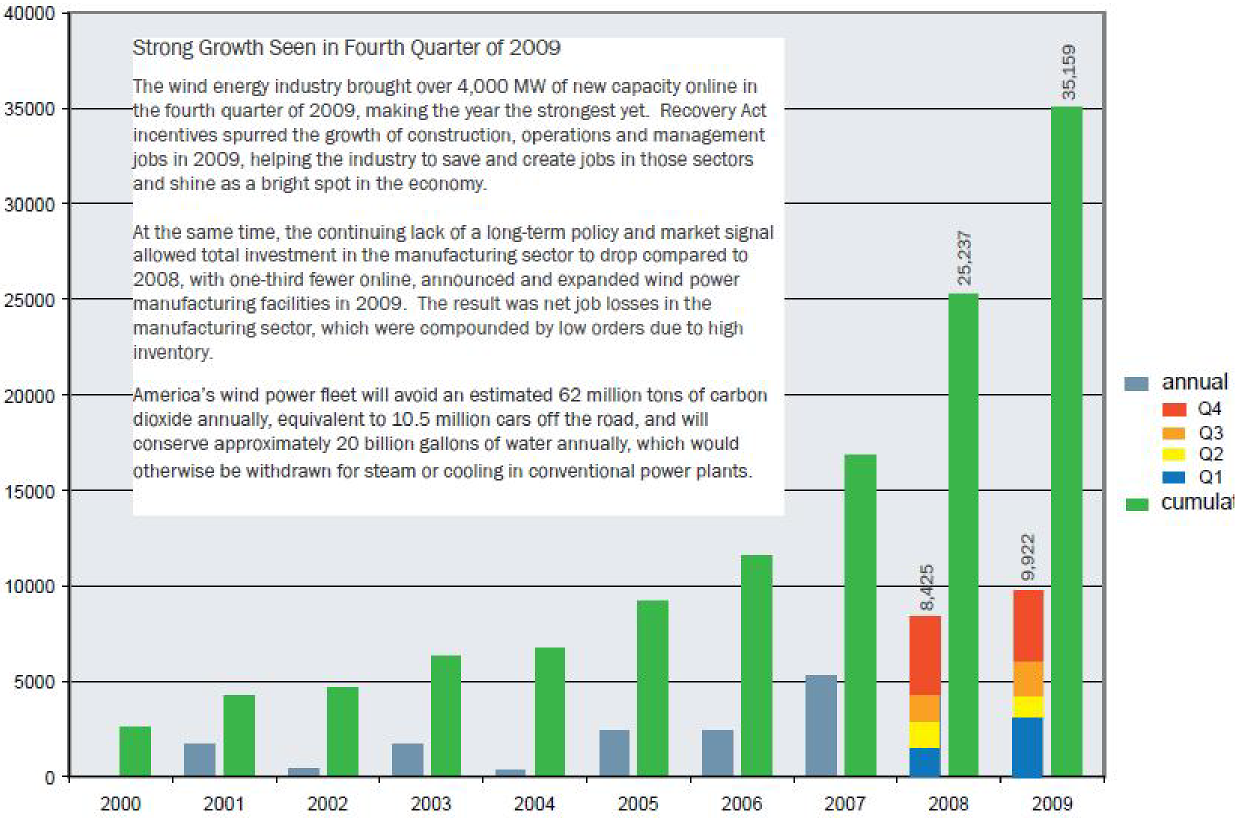
The results of this analysis show the world recoverable oil supply being completely used up by 2060. Although the prediction is based on realistic values and estimates, it is highly unrealistic to assume all recoverable oil would actually be produced. The primary reason for this is simply economics, as the remaining oil supply becomes increasingly difficult and expensive to produce from as it becomes smaller. One important conclusion can be made from this fact alone. Since production would decrease and prices increase before all the resource is consumed, a peak in oil production is highly likely before 2060. After this peak, oil will still continue to be produced for an amount of time, depending on exactly how fast production declines. However, oil as a resource will no longer be able to meet the demand for it.

Section 3: Wind Energy Technology and Issues

3.1 Current State of US Wind Energy

The last half decade has seen a revitalization of growth in the United States wind industry. We are now currently in what can be considered the second resonance of wind energy in the US, with 2009 marking the fourth year straight of increasing annual capacity additions. Such a trend has not even been closely matched since the mid 1980's, when the State of California alone brought the total US wind capacity from near zero to over 1,000 MW in the course of just a few years (23). New capacity additions then almost disappeared, as total US capacity grew very slowly to about 2,500 MW by the year 2000. Growth then began to pick up again around 2000, only to drop back down a year later. This pattern repeated itself in the following few years until finally stable growth began in 2005.

Figure 27: US Wind Capacity Trend (MW) (23)



Strong Growth Seen in Fourth Quarter of 2009

The wind energy industry brought over 4,000 MW of new capacity online in the fourth quarter of 2009, making the year the strongest yet. Recovery Act incentives spurred the growth of construction, operations and management jobs in 2009, helping the industry to save and create jobs in those sectors and shine as a bright spot in the economy.

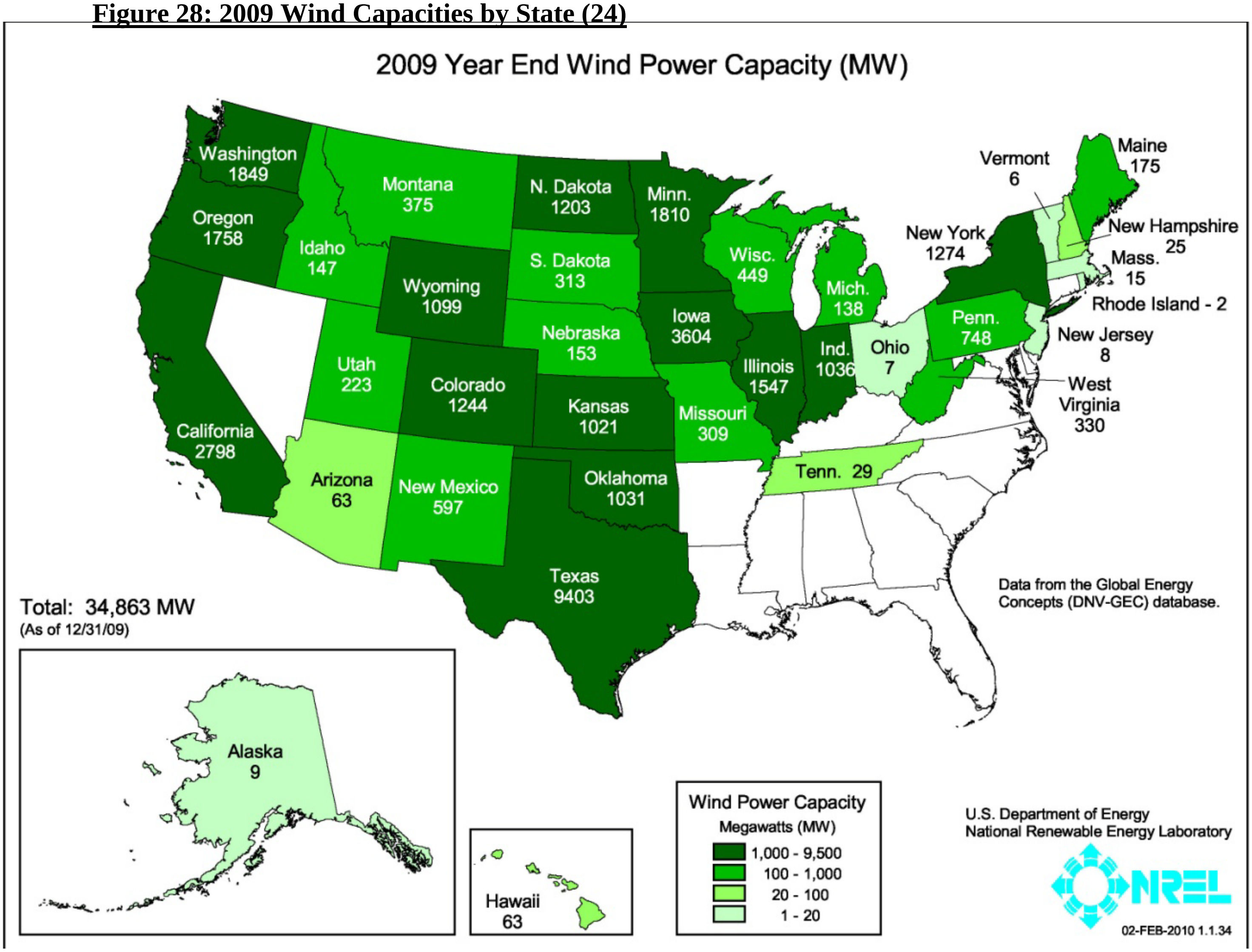
At the same time, the continuing lack of a long-term policy and market signal allowed total investment in the manufacturing sector to drop compared to 2008, with one-third fewer online, announced and expanded wind power manufacturing facilities in 2009. The result was net job losses in the manufacturing sector, which were compounded by low orders due to high inventory.

America's wind power fleet will avoid an estimated 62 million tons of carbon dioxide annually, equivalent to 10.5 million cars off the road, and will conserve approximately 20 billion gallons of water annually, which would otherwise be withdrawn for steam or cooling in conventional power plants.

Since 2005, US wind power capacity has experienced near exponential growth, bringing the total to over 35 GW at the end of 2009 (see chart above). This is quite amazing seeing as the increase from 2009 alone is greater than the total capacity just four years earlier in 2005.

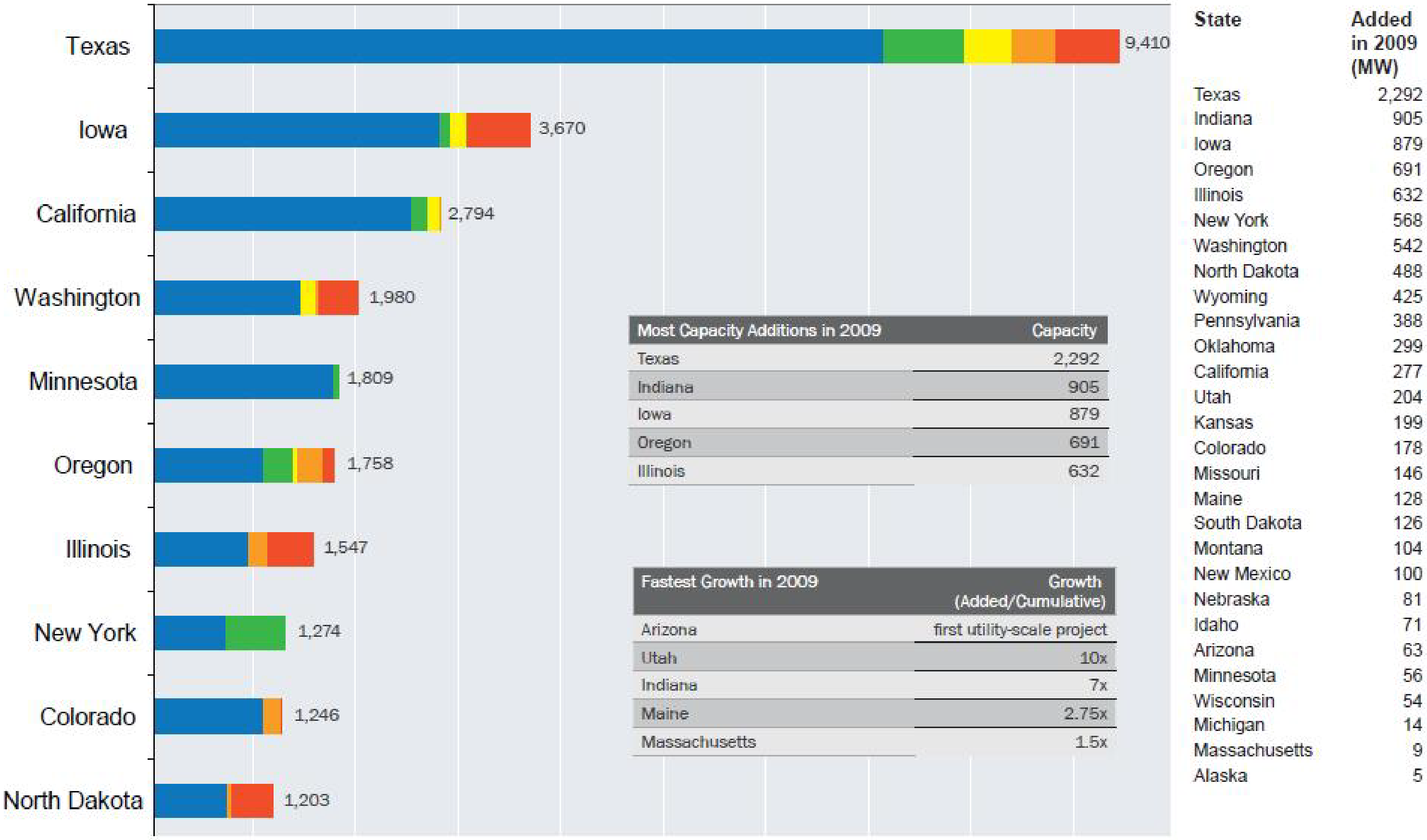
As described previously, California was certainly the birthplace of wind energy in the US, and continued to dominate the market for well over a decade. However, recent growth in wind capacity has come from many states across the country. In fact, around 35 states currently have utility scale wind turbine installations, with 14 totaling over 1,000 MW in capacity each, as can be seen in the figure below.

Figure 28: 2009 Wind Capacities by State (24)



Texas has clearly taken a large lead over all other states, and will soon surpass the 10 GW mark with the completion of current under construction projects. Interestingly, the long time leader California has fallen behind, and only remains in the top three due to its large head start. A look at recent additions at the state level reveals where the real growth is taking place.

Figure 29: Installed Capacity by State, 2009 (23)



Most Capacity Additions in 2009	Capacity
Texas	2,292
Indiana	905
Iowa	879
Oregon	691
Illinois	632

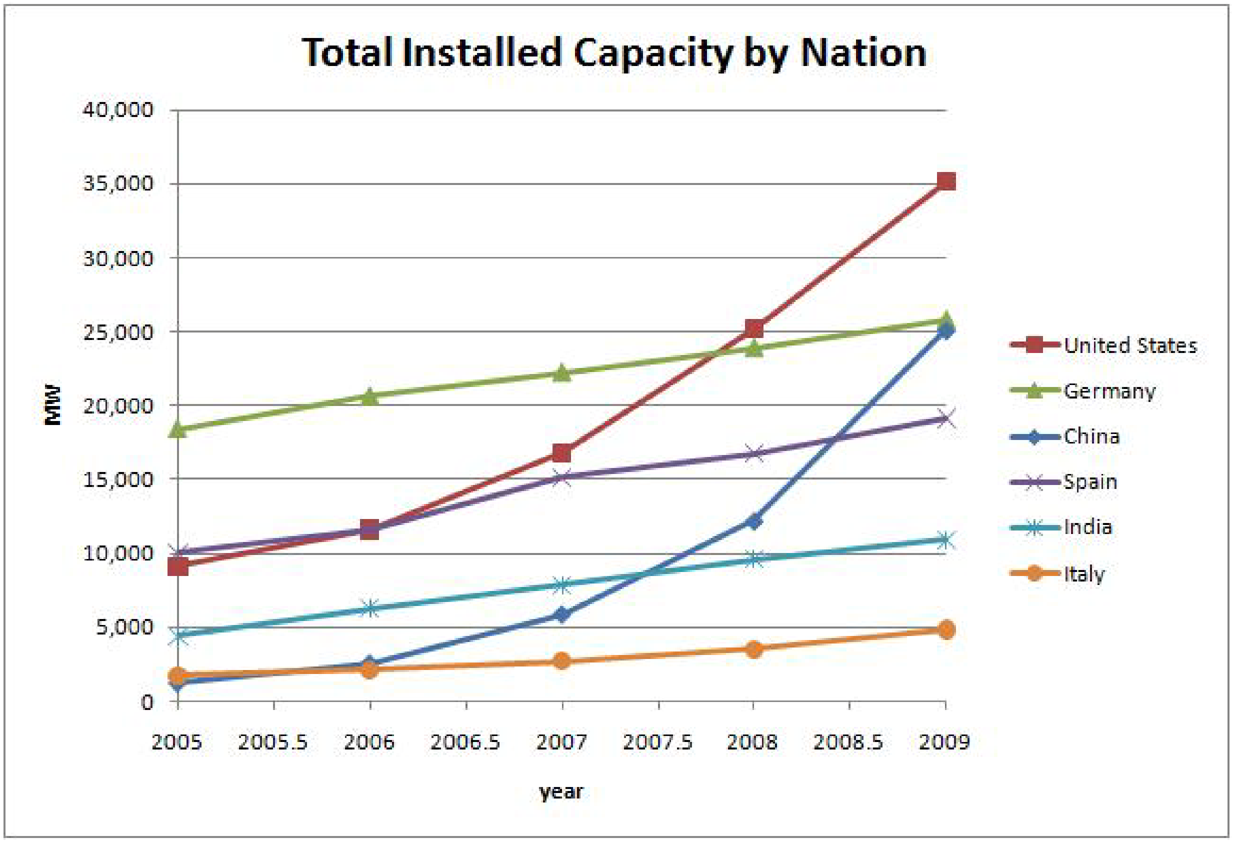
Fastest Growth in 2009	Growth (Added/Cumulative)
Arizona	first utility-scale project
Utah	10x
Indiana	7x
Maine	2.75x
Massachusetts	1.5x

State	Added in 2009 (MW)
Texas	2,292
Indiana	905
Iowa	879
Oregon	691
Illinois	632
New York	568
Washington	542
North Dakota	488
Wyoming	425
Pennsylvania	388
Oklahoma	299
California	277
Utah	204
Kansas	199
Colorado	178
Missouri	146
Maine	128
South Dakota	126
Montana	104
New Mexico	100
Nebraska	81
Idaho	71
Arizona	63
Minnesota	56
Wisconsin	54
Michigan	14
Massachusetts	9
Alaska	5

The blue represents the cumulative capacity up to 2009, and the other colored bands represent the capacity additions for each quarter of 2009. It is no surprise now how Texas has taken such a huge lead, with 2009 additions greater than the total capacity of all but two other states. It may also seem somewhat ironic that the state synonymous with the US oil and gas industry has embraced wind energy to such an extent. One factor that makes Texas unique may also help explain its rapid wind generation growth, which is that Texas lies almost entirely within its own electric grid interconnection. Though the entire US is in essence interconnected, there exist three separately managed zones or interconnections on the grid; one consisting of the eastern states, one consisting of the western states through the Rocky Mountains, and then Texas by itself. It is a logical argument that the simplicity of managing electricity generation in one state only might allow the Texas interconnection to focus more on developing new generation projects.

The recent unprecedented growth of wind power in the US has also brought about another milestone. As of 2008, the US surpassed Germany, the previous leading nation, in total installed capacity. For many years, Europe was the clear leader in wind energy. However, the US is now the world leader, with growth rates much greater than its European rivals. This may not last long though, as China, a nation which has demonstrated record breaking growth in many areas, is not far behind the US capacity and may soon surpass it. A comparison of the top 6 nations by installed capacity is given below.

Figure 30: Installed Capacity by Nation, 2009 (25)

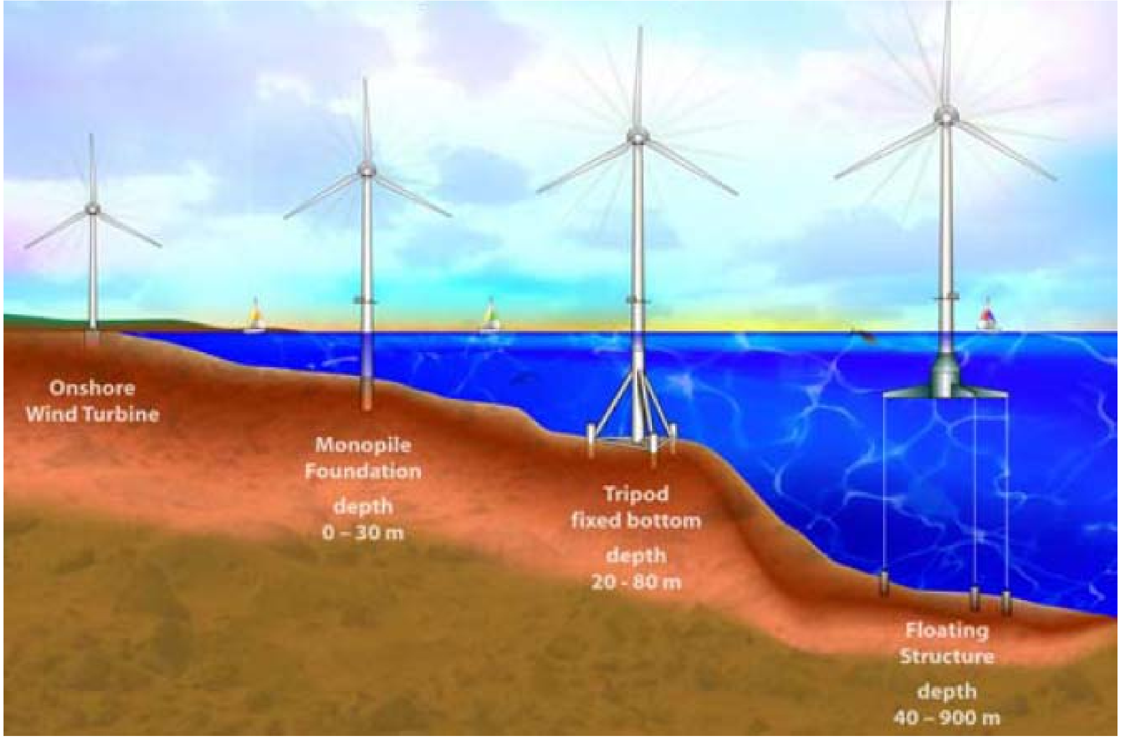


3.2 Alternative Wind Technologies

3.2.1 Offshore Wind Energy

Wind energy potential is limited by the amount of suitable space available to build turbines on. One new solution to this limitation is to build wind turbines offshore in ocean waters. Building offshore wind turbines can be a very effective way to harness wind energy. Winds over bodies of water, particularly the ocean, have a significantly higher mean wind speed than those over land, and are also much more consistent in maintaining these speeds. In addition, there is less turbulence over water, due to the smooth surface geometry, resulting in steadier gusts and less wear on turbines. In the ocean, farms consisting of large turbines can be constructed and operated away from populated areas, and yet remain close enough that transmission costs are not too high. The idea of putting wind turbines offshore is still relatively new compared to land based turbines. The first offshore wind project was built in Europe in 1991. Since then, as of April of 2009, there were only 33 total projects operating in 8 countries, all in Europe. At the end of 2008, out of over 120,800 MW of wind generating capacity around the world, only about 1,471 MW were from offshore turbines (26). The main reason for this difference is due to the fact that present capital costs for an offshore project are higher than the costs for onshore development. Costs of offshore turbines increase rapidly as water depth, wave height and distance from the shore increase, for obvious reasons. In addition, severe weather conditions and corrosion from the salt water environment require stronger, more durable turbine materials and more maintenance attention which in turn drives up costs (26). Most existing offshore turbines are located in shallow areas, less than 30 meters deep, which makes construction and maintenance possible using existing equipment and techniques. However, the U.S. is exploring deep water turbines more and more as many of the coastal waters are greater than 50 meters deep (27). There is currently little information available on the price of offshore turbines, but capital and maintenance costs could potentially be twice those of onshore turbines for an offshore turbine in deep waters. Offshore turbines can be fixed directly to the sea floor, or the turbine can float near the surface and be attached to solid ground by tethers. Several different types of offshore turbine designs are shown in Figure 31.

Figure 31: Offshore Turbine Designs (27)

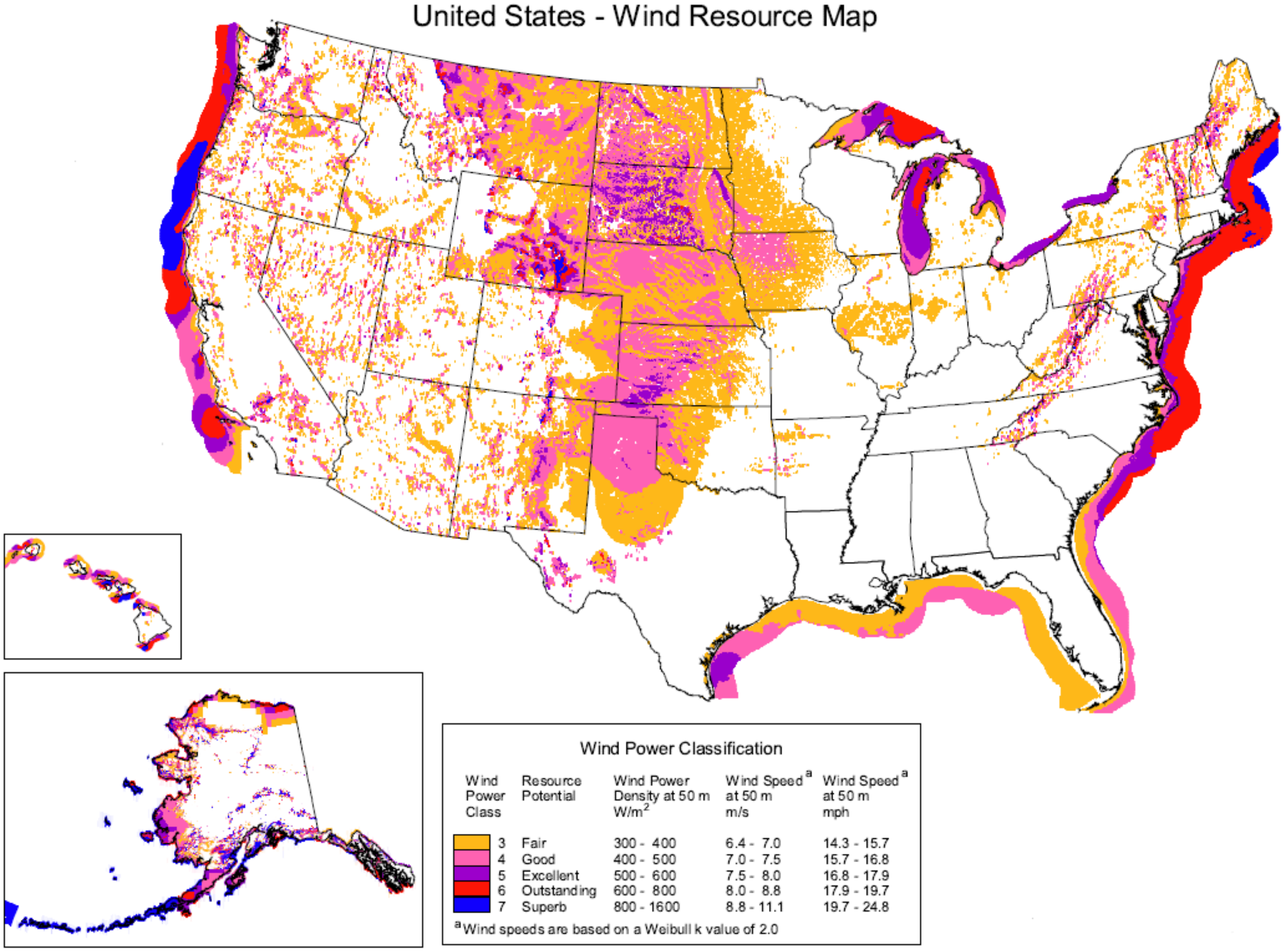


This image shows possible offshore turbine designs at different water depths.

These offshore turbines look to make up for increased capital and maintenance costs with higher energy output from stronger winds and a greater capacity factor. However, there are still many unresolved issues preventing further progress of offshore wind turbines. These are typically concerned with how these machines will affect things like fishing, shipping, and the marine ecosystem. From research and evidence gathered from successful offshore projects, interference with shipping is minimized by simply allowing open lanes of appropriate width between turbine locations. Interference with fishing is also expected to be minimal as turbines take up little space underwater. Small studies have shown that schooling fish have a natural tendency to navigate around underwater obstacles, and thus should not be adversely affected by even large groups of turbines. In terms of the overall marine ecosystems, thus far projects in

Europe have not shown much of a negative impact on marine life, but further research is needed to determine the full long term effects (26, 27).

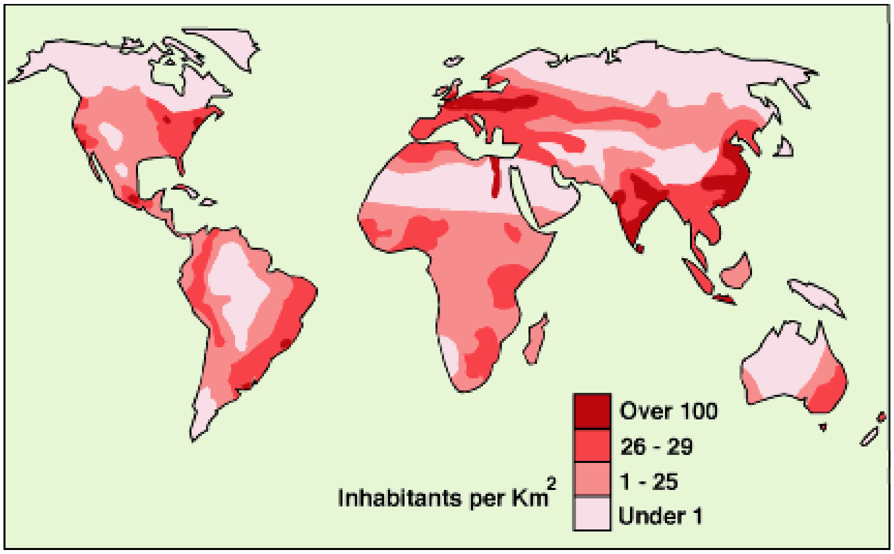
Figure 32: US Wind Resource Map (28)



The map above, from the U.S. Department of Energy National Renewable Energy Laboratory, shows average annual wind power estimates at a height of 50 meters in the United States. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

In the map above, it is very clear how significant a resource offshore wind is in the US. Almost the entire eastern sea board from Maine to South Carolina boarders on “outstanding” wind zones. Turbines in the outstanding and superb wind power areas could harness energy very efficiently, with capacity factors of 50% or more, much higher than the 25 to 35% capacity factors that most onshore wind turbines can manage (27).

Figure 33: World Population Density (29)



From the world population density map it is easy to see why Europe is the leader in offshore wind projects. In Europe, there are not many large, unoccupied land areas on which to build wind farms. Some of Europe's largest population centers are located close to or on a body of water, meaning that the energy harvested by offshore wind farms will not have to be transmitted very far to reach the areas with the most electricity demand. As Europe continues to build wind turbines, more and more of them will likely be located offshore and they will be a steady and efficient provider of clean energy for decades to come.

When you compare the U.S. wind resource map and the population density, you see that the bulk of strong onshore winds in the United States are found in the middle of the country where the population density is low. Most of the America's largest population centers, like Europe, are found on or near bodies of water such as New York, Philadelphia, Boston and Miami on the Atlantic, Chicago and Detroit on the Great Lakes, and Los Angeles on the Pacific. Near these large cities there is not much open area in which to build wind farms, and to build them further from the city means increased costs in the transmission of the energy to high demand centers. If wind farms can be built off the shores of areas with large population densities, then the reduced transmission costs along with the increased capacity factor could compensate for the greater expense of offshore construction. Currently, no commercial offshore wind projects have been built in the U.S. There are several, however, that have been proposed and that are moving through the development process. One proposed project is to be based off the shore of Cape Cod in Massachusetts.

Based on the U.S. Department of Energy's 20 percent wind energy by 2030 scenario, researchers envisioned offshore wind providing 54 GW of capacity out of the 300 GW total from wind, or 18 percent of total wind power being provided by offshore resources (26, 30). In order for these estimates to be brought to fruition, there must be more research and development in this field. Offshore turbines currently face challenges due to their high capital costs, and the fact that there is little experience held in this area by US wind companies. Nevertheless, offshore wind energy certainly could be an effective and important energy provider for the United States in the near future.

3.2.2 Jet Stream Wind Energy

One of the largest issues preventing wind power from supplying large percentages of electricity is that the wind is not a constant resource. Near the ground, wind speeds are variable and very low compared to the constant gusts produced miles over head by the jet streams. There are two jet streams in the Earth's atmosphere. The "polar jet stream" is found over the mid-latitudes at altitudes of 7-12 km. The “sub-tropical jet stream” is the weaker of the two and is found near ± 30º at altitudes of 10-16 km (31). These jet stream winds are up to ten times stronger than gusts near the surface and they are much more consistent (although not completely constant). The jet streams are bands of strong winds that flow from west to east and sometimes to the north and south between the boundaries of hot and cold air as shown in the figure below. They are created when the pressure difference between air masses creates a funnel effect.

Figure 34: Jet Stream Diagram (32)

These high-altitude winds are the largest concentrated source of renewable energy on Earth. The total wind energy potential held in jet streams on average is around 100 times the global energy demand (33). Theoretically harnessing only one percent of this energy could supply the world with power, however unrealistic it may be. Another advantage to harnessing high-altitude winds is that there is no visual or noise intrusion such as that associated with ground based wind farms. Currently, there are a large number of technologies that are in the design and development stage, but none have been tested or produced electricity on a large scale yet. There are two main designs that will be described.

The first design to harness jet stream and other high altitude winds is a tethered kite design. In this design, one or more kites are tethered to an electrical generator on the ground. In this design, when the kite is carried upwards by the wind, the tether is drawn out, generating electricity. The energy generated is the difference between energy generated in the traction phase, and the energy used in recovery. Another kite design consists of several kites that are attached in a carousel configuration and generate electricity as they are blown in a circle. However, these technologies are designed to be operated at an altitude of only around one kilometer, compared to the altitude of about 10km required in order to harvest jet stream energy (31, 34).

Figure 35: Carousel Kite Design (35)

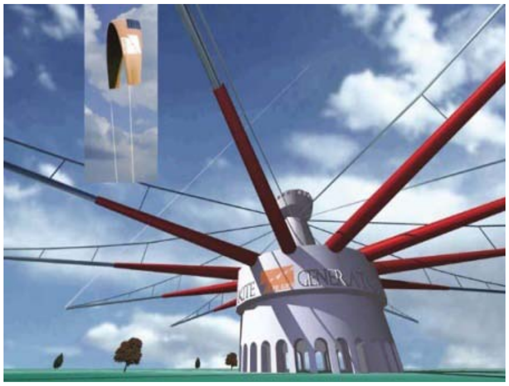
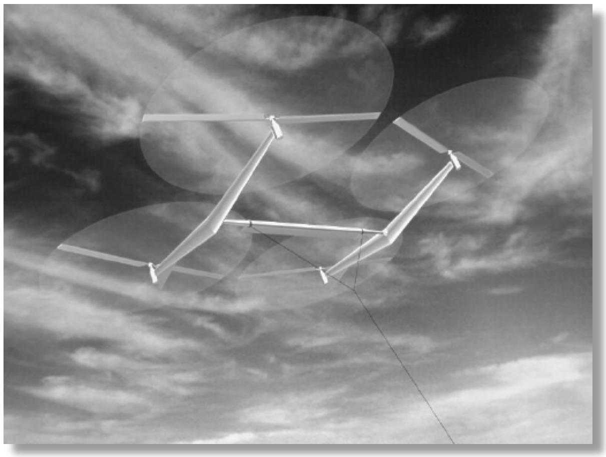


Figure 36: Tethered Kite Design (36)

The alternative to the kite design is one in which the electricity is generated in mid-air and then transmitted through a wire to some sort of battery below. In this design, several motors are mounted on a frame. The rotors are turned by the wind, and in addition to generating excess energy, they provide the lift to keep the machine in the air. With this design, sometimes energy must be transmitted from the battery to the machine to keep it aloft when the wind is slow. These devices are designed to be operated close to the jet stream around 10 km in altitude (31, 34).

Figure 37: Flying Rotorcraft Design (34)



Using data compiled over several decades, wind power density was observed over the five largest metropolitan areas in the world: Tokyo (33.2 million people), New York (17.8), Sao Paulo (17.7), Seoul (17.5), and Mexico City (17.4). Of these five cities, Tokyo, Seoul, and New York are the ones whose wind power density is most influenced by the jet streams. The high-altitude resources over these cities are excellent, with wind power densities greater than 10 kW/m^2 for more than 50% of the time at an altitude of around 8 km. Mexico City and Sao Paulo on the other hand are located at tropical latitudes, and are rarely affected by the polar and sub-tropical jet streams and thus have lower wind power densities than the other three cities$_{21}$. Therefore, there must be great care put into choosing locations for high-altitude wind farms that have the greatest wind power density.

There is still very much work to be done before these high altitude wind farms will be viable commercially, if they ever will be. Some work will need to be done to determine what risk there is for birds and airplanes that may fly close to the devices. Another hot issue with this and other wind energy technologies is energy storage, which will be discussed in a later section. There is also trouble in finding the right materials for the tether in flying rotor generators. The tether must be sufficiently light weight to be easily kept aloft yet must also be able to efficiently conduct large amounts of electricity. In addition to these technological limitations, there is also a question of whether or not using large amounts of wind in energy production could affect the Earth's climate. If the jet stream circulation is significantly altered, then it could lead to increases in sea ice cover across the Earth and decreases in mean surface temperature and total precipitation (31). The impacts will likely be small enough to ignore unless a scenario arises where high altitude wind harnessing is implemented on a huge global scale. More research on possible climate impacts should be looked into as the technology continues to grow. Since this technology is new and unproven commercially, initial design and construction costs are very substantial, making these systems unfeasible at the moment. The tapping of high-altitude winds is not the immediate solution to our energy problems, but over the next several decades gradual integration of these systems into the grid in addition to continued technological advances could make high-altitude winds a reliable source of renewable energy.

3.2.3 Low Speed and Alternative Turbine Designs

Engineers and scientists continue to design new interesting ways to harness wind energy, some more practical than others, but all can potentially help the wind industry by providing diversification. One area that researchers are interested in is low speed turbines. Most turbines don't engage unless wind speeds are 10 mph or more, which means a significant amount of energy from low speed winds is wasted. By making turbines much smaller and lighter, about 95 pounds for one particular 6 foot rotor diameter turbine, the blades are able to be propelled by weaker gusts, as low as 2 mph. This small turbine, priced at $4,500, is meant to be used on rooftops in residential areas where trees and buildings can block much of the wind. According to the company, one of these fan-like turbines can generate 2,000 kilowatt-hours in a year for a home with a very good wind resource, an average wind velocity of between 12 and 15 mph at a height of about 30 ft, according to the company (37). That 2,000 KWh is around 20 percent of the electricity used by the average home in a year, which could save the owners around 200 dollars per year with electricity prices of 10 cents per kilowatt-hour, meaning it would take more than 20 years to pay off the turbine. That turbine is shown below.

Figure 38: Low Speed Turbine (37)

This vertical axis design in figure 39 is another low speed turbine; this particular turbine is 30 feet tall and is capable of providing 2,000 KWh per year, the same as the turbine in figure 38.

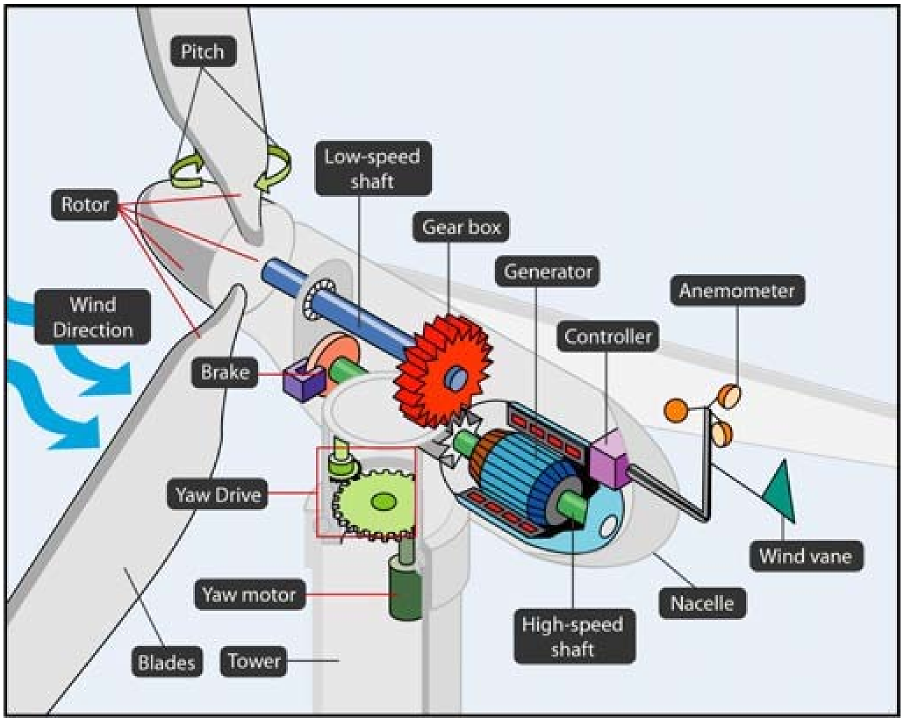
Figure 39: Vertical Axis Turbine (38)

<u>Figure 40: Highway Turbine (39)</u>

This turbine design was proposed by a student from Arizona. The overpass turbines are spun by wind speeds of at least 10 mph caused by the disturbance of cars driving by. Each of the turbines could theoretically produce enough energy to power a small home (39).

3.3 Wind Turbine Mechanics

Figure 41: Wind Turbine Diagram (40)



The basic components of a modern 3-bladed turbine were shown in figure 41. This is one particular design, though most of the part types are standard for an average sized turbine or larger. Below are functions of the various components of a wind turbine (40):

Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Blades: Most commercial turbines have either two or three blades. Wind blowing over the blades creates a pressure differential, creating lift and causing the blades to rotate.

Brake: A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies and prevent damage to the unit. This is often necessary when strong gusts are prevalent.

Controller: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour and shuts off the machine around 50 to 60 mph. Turbines do not operate at very high speeds because the resulting torsional forces can cause failure of mechanical components.

Gear box: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm. Direct-drive generators operate at lower rotational speeds and don't require gear boxes.

Generator: Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.

High-speed shaft: Drives the generator induction coils. It is typically kept at a constant rotational speed via the gear system so that the output electricity frequency remains stable.

Low-speed shaft: The rotor turns the low-speed shaft at about 10 to 20 rotations per minute for typical operating conditions.

Nacelle: The nacelle sits atop the tower and contains the gear box, low and high-speed shafts, generator, controller, and brake systems. Its profile is very aerodynamic as to prevent the creation of turbulence behind the turbine blades.

Pitch: Blades are rotated, or pitched, to adjust the lift force and keep the turbine rotating at optimal speeds. Pitching can also be used to intentionally stall the blades in the case of strong winds.

Rotor: The main fixture where the blades and shaft are connected.

Tower: The tower is the main supporting structure, with a strong base usually of concrete. The center is usually hollow to allow for maintenance access of internal turbine components.

Wind direction: Turbines can be designed to be either upwind (facing the wind) or downwind (away from the wind).

Wind vane: Measures the incoming wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive: The yaw drive is used to keep the plane of the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive as the wind naturally orients the rotor downwind.

Yaw motor: Powers the yaw drive.

3.4 Wind Energy Conversion

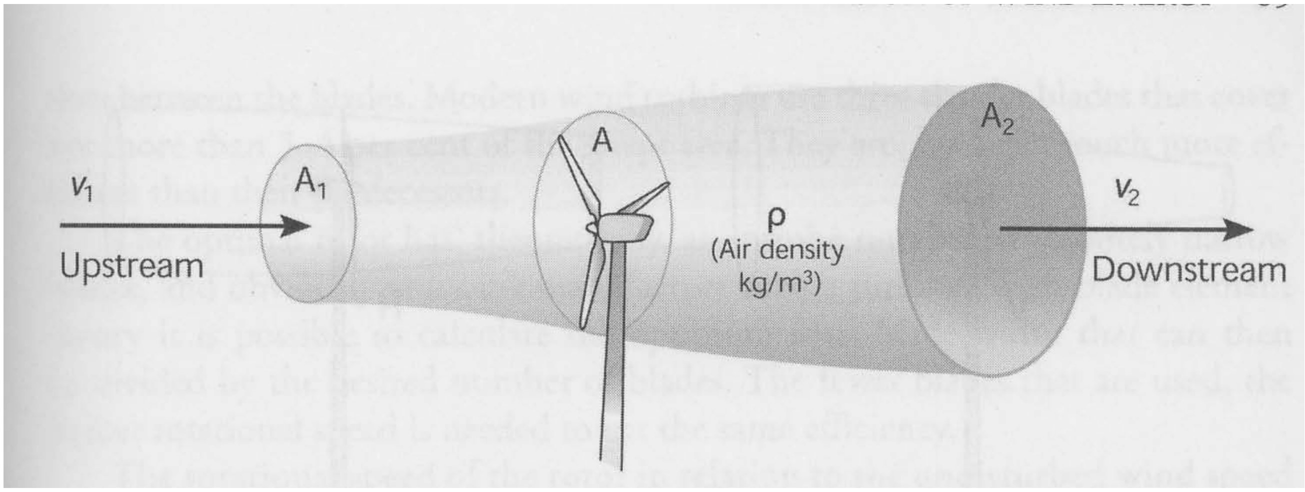
At their fundamental design, wind energy conversion systems are simply machines that can capture the kinetic energy of moving air masses and convert it to other useful forms of energy. Earlier in history, wind mills transformed the wind into other forms of mechanical energy that could do useful work, such as grinding grains. Later, during the agricultural revolution, this mechanical energy was also used to drive the pistons of water pumps on many farms. At present however, wind energy is being used almost exclusively for the generation of electricity.

The flow of energy in any wind energy conversion system (WECS) ultimately starts with the Sun's incident radiation upon the Earth. This is responsible for the differential warming of some air masses which results in temperature differences, or thermal gradients, occurring between distant air masses. In turn, the warmer air masses will have a lower density than cooler ones, resulting also in a pressure difference between the air masses. It is this pressure difference which serves as the driving force for the movement of air, what we know as wind. The different air masses have a natural tendency toward equilibrium, which is achieved by the movement of air from regions of high pressure to lower pressure. On a global scale, winds also result from the inertial forces created by the Earth's rotation. However, on the local scale, which is most applicable for any WECS, pressure differences are the major driving force of winds.

On a theoretical basis, an ideal wind turbine would be one that extracted all the kinetic energy from an oncoming wind stream and converted it to rotational energy of the turbine system. This scenario is simply a physical impossibility, however. If all kinetic energy was extracted from the wind, the air directly behind the turbine blades would have a resulting velocity of zero. This would cause the suddenly stopped air masses to accumulate behind the turbine and essentially block the flow of any further air. Additionally, any stalled air behind the turbine blades would create additional drag forces on the blades, decreasing their rotational energy. For these reasons, any real, functioning turbine must allow air flow to continue on once it has passed through the rotational plane of the turbine. The objective then becomes obtaining a balance between how much the winds' velocity is reduced and how much energy is extracted by the turbine.

There does however exist a practical limit on wind energy extraction from an ideal turbine. It has been calculated that an ideal turbine can capture no more than 59.3% of the kinetic energy from the wind passing through it (58). The model proving this was derived by aerodynamics researcher Albert Betz in the Early 1920's and has become known as Betz' limit. The model considers a control volume of air in a tube shape which contains the turbine rotor in the middle as pictured below.

Figure 42: Stream Tube (57)



Air only enters the tube via cross section A_1 and only exits via A_2. The velocity of the entering air is given by v_1 and the exiting air by v_2. The model relies on a series of assumptions in order to be valid, and they are as given below (58).

- Homogenous, incompressible, steady state flow
- No frictional drag
- An infinite number of rotor blades
- Uniform thrust over the rotor area
- A non rotating wake
- The static air pressure far upstream and downstream of the rotor is equal to the ambient undisturbed air pressure

The first assumption requires that for any given cross section within the tube, the flow velocity is uniform over the whole area and doesn’t vary with time. Also, the air density must remain constant throughout the tube. The second assumes that the air flow contacting the rotor blades is smooth and doesn’t create any drag forces which would slow the blades. The third assumption is obviously the least practical in reality, but allows the rotor blades to be infinitesimally thin and cover as much area as possible. The non rotating wake means that the tips of the blades do not create any vortices as they pass through the air, which would create drag forces. The final assumption is simply a boundary condition which guarantees continuity at the edge of the stream tube.

3.4.1 Derivation of Betz' Limit (57)

Taking the stream tube from figure 42 as the control volume, conservation of linear momentum is applied to the system of air and the turbine. The air velocity at the turbine blade, not included in the image, will be noted simply as v. By conservation of mass, each cross section must have the same mass flow rate, or time rate of change, given by (59)

$$\dot{m} = \rho A_1 V_1 = \rho A V = \rho A_2 V_2 \quad \text{(eq. 1)}$$

The force exerted by the air on the turbine is cause by the difference in momentum between the entering and exiting air stream and is given by

$$F = \rho A_1 V_1^2 - \rho A_2 V_2^2 \qquad \text{(eq. 2)}$$

And since $A_1 V_1 = AV = A_2 V_2$, the force can be expressed as

$$F = \rho A V (V_1 - V_2) \quad \text{(eq. 3)}$$

The force can also be written as the pressure difference between the flow upstream and downstream the rotor where P_u is the upstream pressure, P_d is the downstream pressure, and P is the ambient pressure, so

$$F = (P_u - P_d) A \qquad \text{(eq. 4)}$$

Using Bernoulli's equation and assumption 6,

$$P + \frac{\rho V_1^2}{2} = P_u + \frac{\rho V^2}{2} \; and \; P + \frac{\rho V_2^2}{2} = P_d + \frac{\rho V^2}{2} \qquad \text{(eq. 5)}$$

Combining these results yields

$$P_u - P_d = \frac{\rho(V_1^2 - V_2^2)}{2} \qquad \text{(eq.6)}$$

Substituting eq. 6 into eq. 4 gives

$$F = \frac{\rho A(V_1^2 - V_2^2)}{2} \qquad \text{(eq. 7)}$$

Comparing and combining equations 3 and 7 gives

$$V = \frac{V_1 + V_2}{2}, \qquad \text{(eq. 8)}$$

which states that the wind velocity at the turbine rotor is the average of the upstream and downstream velocities. Now a parameter termed the axial induction factor, represented as “a”, needs to be introduced. This factor represents the reduction in velocity due to the turbine.

$$a = \frac{(V_1 - V)}{V_1} \qquad \text{(eq. 9)}$$

Combining equations 8 and 9 gives

$$V = V_1(1-a) \quad \text{And} \qquad V_2 = V_1(1-2a) \qquad \text{(eq. 10)}$$

The actual power generated by the turbine, P_T, is equivalent to the time rate of change of the kinetic energy transfer and is given by the product of the mass flow rate and the change in kinetic energy as

$$P_T = \tfrac{1}{2}\rho AV(V_1^2 - V_2^2) \qquad \text{(eq. 11)}$$

Substituting the results from eq. 10 gives

$$P_T = \frac{1}{2}\rho A V_1^3 \times 4a(1-a)^2 \qquad \text{(eq. 12)}$$

The efficiency by which a turbine extracts energy is termed the power coefficient, C_P, and is given by the ratio of the generated power to the theoretical available power.

$$C_P = \frac{2P_T}{\rho A V_1^3} \qquad \text{(eq. 13)}$$

Substituting eq. 12 gives $\quad C_P = 4a(1-a)^2 \qquad$ (eq. 14)

To find the maximum power, the derivative must be taken and set to 0.

$$\frac{d\,C_P}{da} = 4 - 16a + 12a^2 = 0 \qquad a = 1/3$$

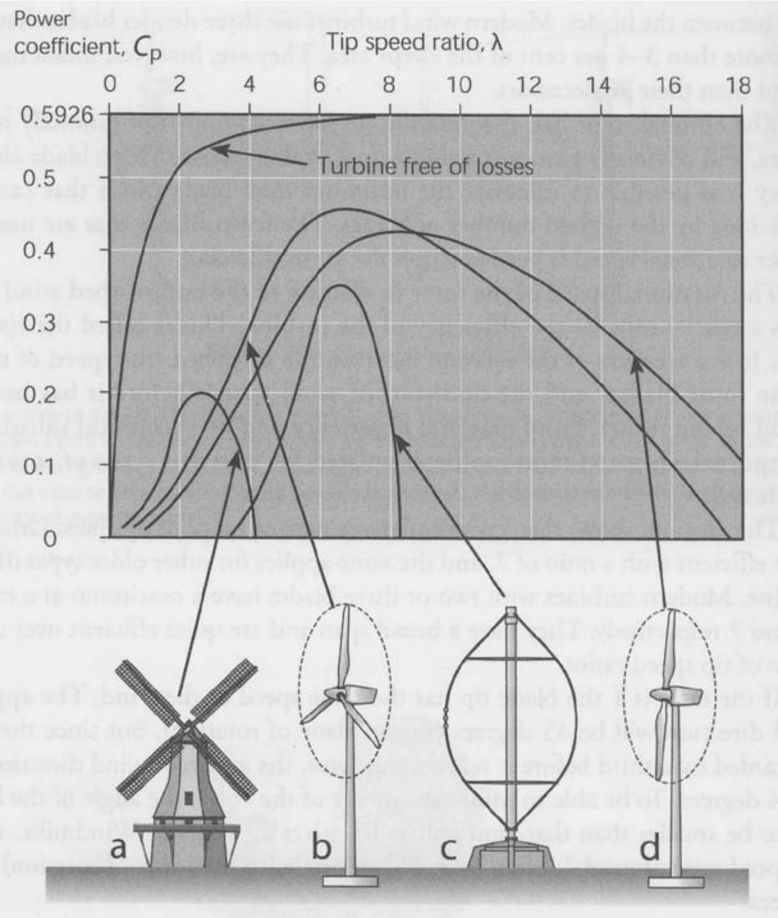
Substituting the value of a into eq. 14 gives

$$C_P = 16/27 \approx 59.3\%$$

Thus the ideal turbine can extract no more than 59.3% of the winds' energy. When the value of 1/3 is used for the parameter a in eq. 10, another interesting result becomes apparent, which is that the wind velocity at the turbine rotor should have lost 1/3 of its initial velocity as it passes through the blades and have lost a total of 2/3 its initial velocity once it has passed the turbine blades (59).

In reality, trying to engineer a turbine to slow the winds in exactly this manner is not an easy task. Modern commercial scale turbines have however come fairly close to achieving this upper limit, and can maintain near-optimum performance over a much wider range of conditions compared to older designs. The figure below compares the power coefficient, which represents the proportion of energy obtained by the turbine, for various turbine designs over a range of conditions.

Figure 43: Power Coefficient vs. Tip Speed Ratio (57)



The tip speed ratio, given by λ, represents the ratio of the turbine blade tip velocity to the velocity of the incident wind; $\lambda = v_{tip}/v_{wind}$. For a fixed rotational speed of the turbine, this means that the longer the blades are, the higher the tip speed ratio will be. From the chart, we can see that the modern three bladed turbine reaches its optimum performance around a tip speed ratio of 7, at which point it is extracting nearly 80% of the theoretical maximum power according to the Betz limit.

3.4.2 Power Output

With the derivation of Betz limit, we can now proceed to predict the power output of a real turbine based on the available wind speed. From basic physics, the kinetic energy of a body is given as$1/2mv^2$. In this case, m is the mass of the air flowing past the turbine and v is its velocity. Since power is the time rate of change of energy, holding the velocity constant and differentiating the expression with respect to time should give the power available from a moving air mass.

$$P = \frac{d}{dt}\left(\frac{1}{2}mv^2\right) = \frac{1}{2}\dot{m}v^2$$

The mass flow rate, $\dot{m}$, can be expressed as pAv, where p is the air density, A is the cross sectional area which the air moves through (specifically the rotor area), and v is again the air velocity. The term Av can be thought of as the volumetric flow rate, with units of m^3/s. Combining results gives:

$$P = \frac{1}{2}pAv^3.$$

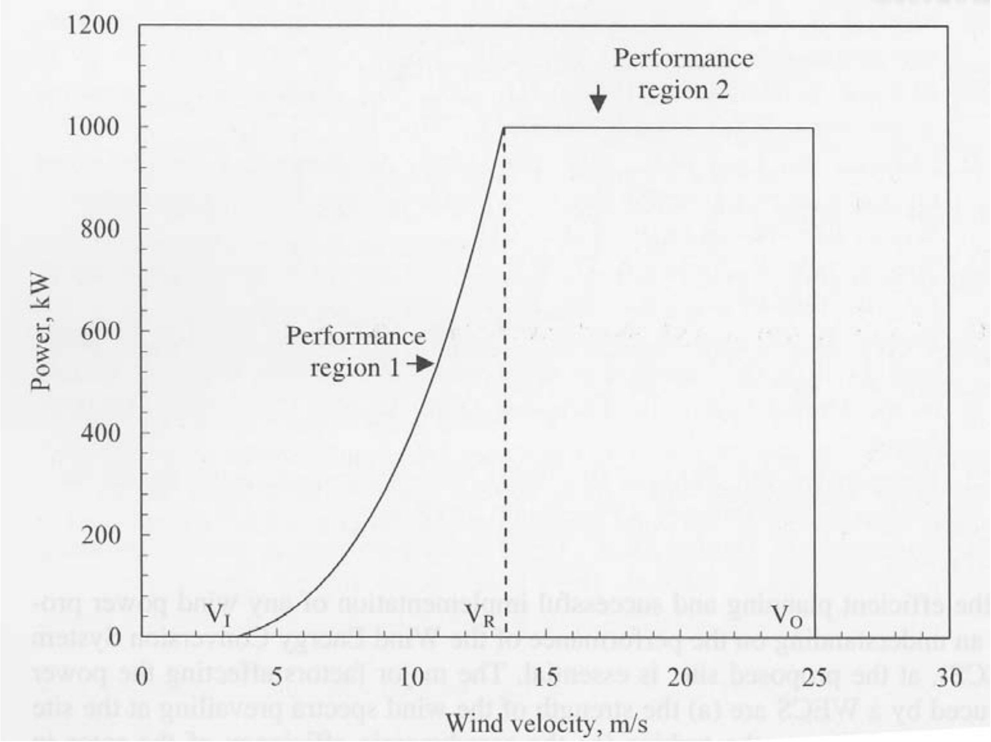
As was previously discussed, no real turbine can capture all of the winds kinetic energy, so this power expression only represents the power available in the wind, not what can be captured by the turbine. To correct this, a constant factor must be added, specifically, the power coefficient C_p, where the maximum value is Betz limit of 16/27.

$$P = \frac{1}{2}C_p pAv^3$$

3.4.3 Performance Regions

Although we now have an accurate equation relating turbine power to incident wind velocity, its applicability must be further limited due to the mechanical limitations of wind turbines. Primarily, the issue is that turbines simply can't operate at all wind speeds. When the wind is too slow, there is not enough energy being transferred to the turbine blades to overcome the internal resistance (friction) of the rotor, and the blades remain stationary. Even if the wind speed is sufficient to turn the blades, some systems are intentionally prevented from operating at low speeds. The reasoning behind this is that power output would be too small and intermittent to warrant the wear which it would cause on the turbine systems. The minimum velocity for which the turbine operates is referred to as the cut in speed, and is denoted as V_I in the graph below.

<u>Figure 44: Turbine Performance Regions (59)</u>



For wind speeds above the cut in speed, the turbine power output begins to increase according to the power equation derived above. This is seen as the cubic curve defining region 1 above, reflecting the cubic dependence on velocity. Power output continues to increase until the wind speed reaches V_R, the rated wind speed. At this speed, the turbine is producing its rated "name plate" power output. Since the turbine generator is running at maximum power at this wind speed, any additional increase in speed will result in the same power output, seen by the flat curve defining region 2. The turbine continues to function at maximum power output until wind speeds approach potentially damaging levels, referred to as the cut out speed, and labeled V_O above. At this speed, the turbine is forced to shut down in order to avoid the excessive stresses which would be created on the turbine components from high wind speeds. This can be accomplished by two primary methods. Some turbines use pitch control systems to rotate, or pitch, the blades out of alignment with the wind, which eliminates the lift forces which were being generated previously, and the turbine ceases its rotation. The other method is accomplished by specially designed turbine blades which create turbulence behind the blades at high wind speeds, and induce aerodynamic stall of the blades.

3.5 Aerodynamics

As seen in the previous section, a simple physical analysis can reveal the practical limits of wind turbine energy extraction. It was even shown that modern turbines are able to come relatively close to reaching this performance limit. However, most of the idealized assumptions made in order to validate the Betz model are far from representing realistic conditions. Therefore, in the design of actual wind turbines, more sophisticated aerodynamic analysis must be used if the turbine performance is to be accurately predicted. This section will seek to outline some of the more advanced theories used in turbine blade design, and describe why they are more accurate. First, though, some basic aerodynamic principles relevant to wind turbines will be explored.

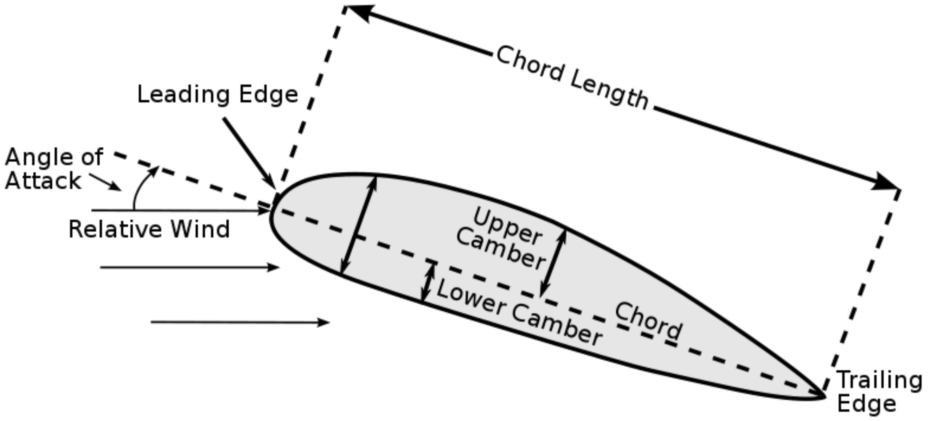
3.5.1 Lift

The basic operating principle of wind turbine blades is the same as that which is used by traditional aircraft; the principle of lift. According to Bernoulli's principle, the pressure exerted by a stream of fluid, in this case air, decreases as the flow velocity increases.

Bernoulli's principle: $\frac{v^2}{2} + gz + \frac{p}{\rho} = constant$, where v is the flow velocity, g is gravitational acceleration, z is elevation, p is pressure and ρ is the fluid density.

If an object moving through the fluid has a shape which forces the fluid to travel a further distance over one of its sides than the other, the fluid must then flow faster over the longer side in order to merge back into a continuous flow at the rear of the object. The side with the faster flow is consequentially subjected to a lesser pressure according to Bernoulli's principle. Therefore, because of the pressure difference between the two sides, a net force referred to as lift is experienced on the object. If the lower pressure side is the top of the object, relative to a downward gravitational force, then the lift force will tend to counteract the downward force on the object due to gravity. In the case of aircraft flight, this lift force generated by the wings must be equal to the gravitational force on the plane during level flight, so that the net sum of forces in the vertical direction is zero. A general shape which acts like a wing by producing lift is known as an airfoil. In fact, early wind turbines used standard airfoil designs which were originally created for use as aircraft wings. These met the necessary objective of achieving lift on the turbine blades, but were not ideal, as will be shown.

Figure 45: Typical Airfoil Design (60)



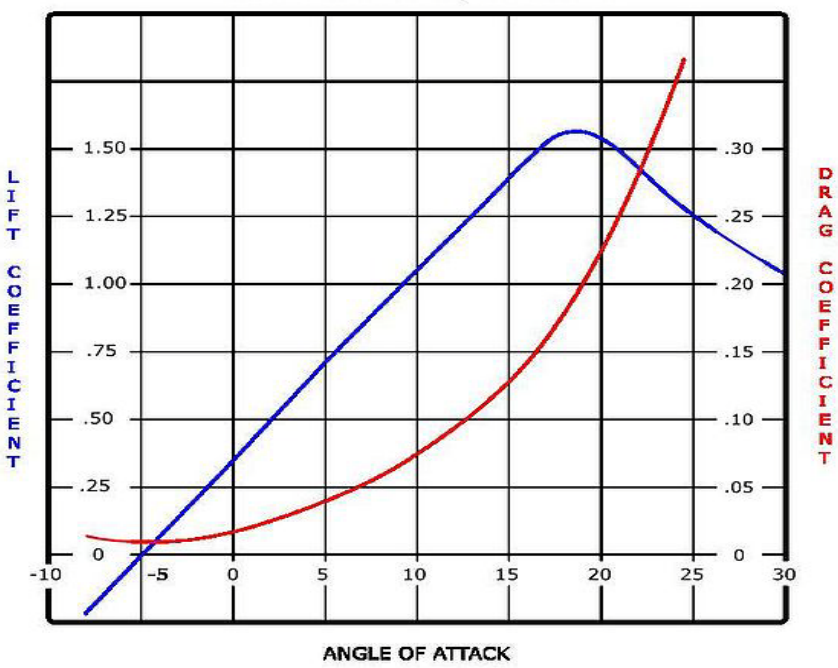
3.5.2 Angle of Attack

For an airfoil design to function as intended and be able to generate lift, the airfoil must be at some angle with respect to the relative wind speed direction. This is referred to as the angle of attack, and is shown in figure 45. It is this angling of the airfoil which creates a path of longer travel on the top surface of the airfoil, allowing the generation of lift force. For a given airfoil design, the angle of attack is the main variable which lift and also drag force are dependent on. Lift and drag forces for an airfoil are given as:

$$Force_{lift} = \frac{1}{2}C_L\rho Av{}^\wedge 2 \qquad Force_{drag} = \frac{1}{2}C_D\rho Av{}^\wedge 2,$$

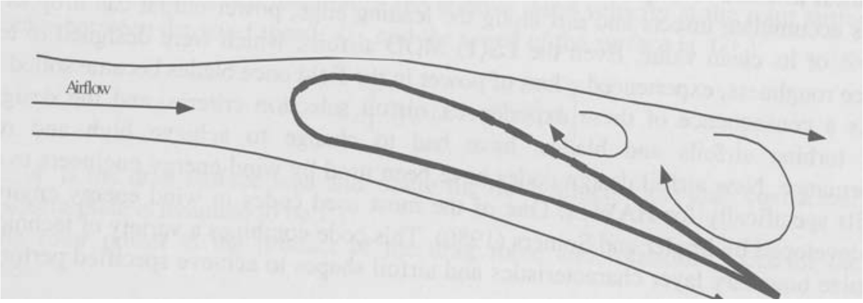
where ρ is the air density, A the plane form area, v the air speed, and C_L and C_D the coefficients of lift and drag, respectively. These coefficients are based on the specific geometry of the airfoil, and vary with the angle of attack, as shown below, making the lift and drag forces ultimately dependent on the angle of attack.

Figure 46: Lift and Drag Coefficients vs. Angle of Attack for Typical Airfoil (62)



The lift coefficient varies nearly linearly up to an angle of attack of about 17 degrees. This occurs since the increased angle causes the air over the top surface to also increase its speed, and in turn the pressure on the top surface is reduced. The drag coefficient tends to increase with the square of the angle of attack. This is caused by the increased force of the air along the direction of the top surface, which is proportional to the square of the velocity. After an angle of about 17 degrees, the lift begins to decrease, however. This is due to an additional effect known as form drag. When the angle is this steep, it becomes difficult for air to flow smoothly along the upper surface, and the creation of turbulence occurs along the back edge of the airfoil, as shown below.

Figure 47: Turbulence Induced Drag (58)

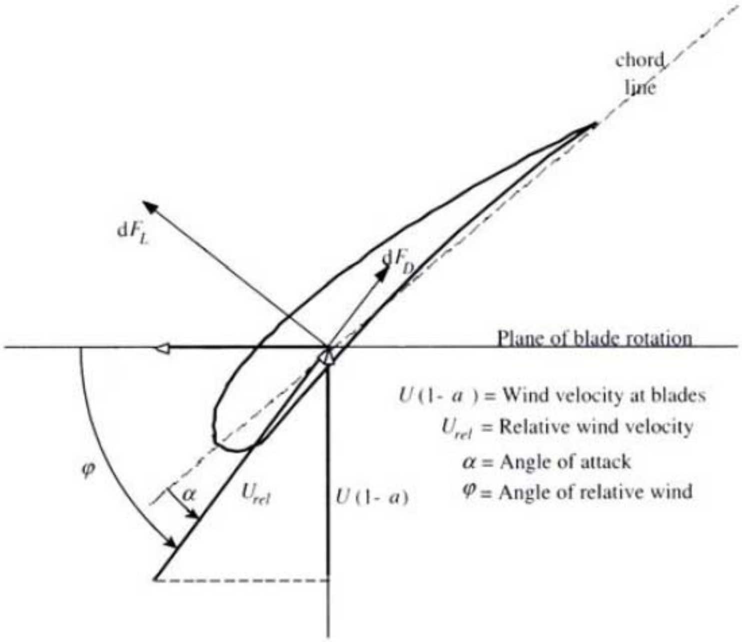


The rough flow characteristics of the turbulent air result in a slower stream velocity on the top edge, thus reducing the effect of lift, which is dependent on a faster air velocity along the top surface.

3.5.3 Blade Twist

The key difference between airfoil performance on an aircraft and its use in wind turbines is the fact that airplane flight is essentially entirely linear in nature, as the entire length of the airfoil experiences the same incoming air velocity. In the case of wind turbine use, this does not hold true. Instead, for any given incident wind velocity in the plane of the rotor, the actual relative velocity of the wind to the turbine blade will vary as a function of the blade radius. This is because the relative wind velocity actually has two components: the incident wind velocity, and the tangential velocity of the blade due to its rotation. This tangential velocity at any point is equal to the product of the radius and the angular velocity of the rotor, so it increases linearly with blade radius. A vector representation of this is given below.

Figure 48: Turbine Blade Cross Section (58)



The angle ϕ shown is the angle between the direction of blade rotation and the relative wind velocity, which would be 90 degrees at the rotor hub. Since the incident wind velocity is approximately constant across the rotor for any given time, the increase in the tangential velocity of the blade as radius increases causes the direction and magnitude of the relative wind velocity to also increase. This results in ϕ becoming smaller as blade radius is increased.

As discussed earlier, the angle of attack is measured between the airfoil (blade) and the relative wind velocity. Since the relative wind velocity is now seen to change with blade radius, the angle of attack would also change as a result. This would create a problem for a traditional airfoil design in which the profile is constant along the length. The angle of attack would be greatest at the blade base, and then gradually decrease as the angle of the relative velocity became smaller along the blade radius.

In order to generate the maximum amount of lift, the angle of attack must be kept fixed at its optimum value for any given wind speed. To accomplish this, the blade must be kept at a fixed angle to the relative wind velocity, even as the relative wind velocity changes. This is achieved by designing a blade with a profile which “rotates” along the blade axis as radius increases, as shown below.

Figure 49: Turbine Blade Twist (57)

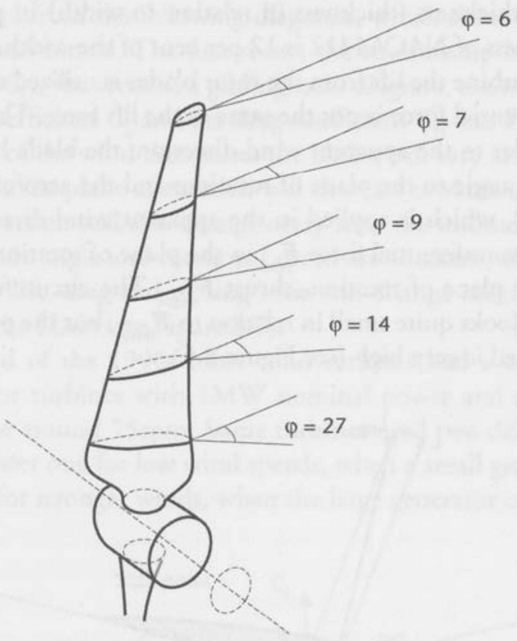


Figure 8.4 *Apparent wind direction along a rotor blade with a wind speed of 9m/s*

Source: Södergård (1990)

3.6 Use of Control Systems in Modern Wind Turbines

Modern utility scale wind turbines consist of very large and complex mechanical systems. The ever increasing trend in turbine size and specifically hub height has led to modern turbines being subjected to extremely large loadings during operation. This is due to two basic facts. First, that larger turbines inherently have a larger surface area, which exposes them to a greater total loading for any given wind conditions. Second is the fact that wind velocity generally increases with height from the ground, and larger turbines are centered at higher heights from the ground. Since the energy contained within the wind (kinetic energy) is proportional to the square of velocity, a doubling of wind speed would lead to an increase in wind energy by a factor of four, which would in turn cause the forces exerted by the wind on the turbine to increase by the same factor. One additional consideration for larger wind turbines is the material stiffness, or flexibility. As blade length increases, flexibility also tends to increase, allowing greater bending displacements and motion of the blades when subjected to large loading forces. These displacements are undesirable, as they cause fatigue of the blade material, and therefore should be minimized if possible. Turbine support towers also become subjected to large loadings during operation, and can suffer similar fatigue effects as turbine blades, as well as undergo forced vibration. On the inside of a turbine, large torsional loadings and oscillations can also be found in the drive train, due to excessive varying torque. All of these situations create potential problems for the safe and reliable operation of modern large scale wind turbines, so it is highly desirable to lessen the impact of these effects.

In this section, we will investigate current techniques being explored to reduce fatigue loads on wind turbines during operation. This is accomplished through the use of closed loop feedback control systems. Older wind turbine technologies have in fact been using control systems for quite a while. However, they have proved non ideal for dealing with the complex loads experienced by modern large scale wind turbines. These older systems used methods of classical control theory, specifically PID (or Proportional-Integral-Derivative) control in SISO (Single Input Single Output) loops, to manage the dynamic loadings on turbines. Unfortunately, these methods are limited by their ability to only deal with single input and single output systems. In order to meet multiple control requirements, separate closed loop systems would be necessary for each output which is desired to be controlled. This inherently leads to issues in the design of separate systems which ultimately interact with one another. One of the biggest concerns for such a setup is the overall system stability. Stability refers to the tendency of the system response to either converge for a given input (stable), or diverge towards infinity (unstable). It is a general rule that greater numbers of closed loop elements within a system tend to increase the possibility of instability.

There does, however, exist a solution to both the turbine loading and control stability problem. This is possible through the use of modern advanced state space control methods. These methods use linearized models represented as systems of differential equations in the time domain which are coupled via matrix representation. This makes it much easier to take into account the multiple inputs and outputs which are necessary to achieve the desired system response and stability. Later, we will specifically analyze one particular control system which was developed by the NREL (61, 62) (National Renewable Energy Lab) for experimental purposes. The target application for the design was their onsite “Controls Advanced Research Turbine” or CART. To understand how the system functions in principle, the measured variables (input) and the parameters to be monitored and controlled (output) are described below.

3.6.1 Independent Blade Pitch Control

As part of the standard functionality of most modern wind turbines, each blade is able to pivot about its attachment to the hub. This rotation is referred to as blade pitch, which we'll call α. The main purpose of altering blade pitch during operation is to control the amount of lift and drag forces which the turbine blades generate, F_L and F_D respectively. These of course in turn affect the rotational velocity of the rotor unit, Ω. The relations are given as: $\Omega \propto F_L, F_D \propto \alpha, v$ where v is the wind velocity. When winds are below the turbines rated wind speed, blade pitch is held constant in order to maximize lift and, accordingly, rotor rotational speed. However, in what is known as "performance region 3" where winds are above the rated wind speed, turbine blade pitch is adjusted in order to maintain constant rotor speed, and accordingly generator shaft speed. This is necessary, because once a turbine has reached its rated wind speed, it is generating its maximum power output, and so additional generator speed is unnecessary and would overload the system.

The above description of blade pitch control is relevant to almost all modern utility scale turbine designs. In this section, though, additional secondary uses of blade pitch control to reduce fatigue on turbine components are investigated. By making minute adjustments to blade pitch, it has been found that the effects of wind shear across the rotor plane can be reduced, and active damping can be added to the first fore-aft bending mode of the turbine tower.

3.6.2 Asymmetric Wind Loading

In most realistic scenarios, the flow pattern of wind is not necessarily uniform. Instead, velocity varies with position over the cross sectional area of the rotor plane. A typical scenario in which this occurs is wind shear. As discussed previously, wind speed usually increases with height above the ground. Since turbine rotor diameters can be quite large, on the order of 100-125 meters, the difference in wind speed between the bottom and top of the rotor can also be quite significant. Such a situation with greater wind speed at the top of the rotor plane would in turn cause an uneven loading of the rotor, with greater force concentrated on the upper half of the rotor. This would result in the presence of significant stresses and fatigue on the rotor and its attachment at the hub. To prevent this from occurring, the control system is designed to compensate by slightly pitching the blades as they pass through the upper part of the rotor arc, therefore less lift is produced on the blades. If this is done correctly, then the lift forces generated on each blade should be essentially equal at all times, resulting in an even load distribution on the rotor plane.

3.6.3 First Fore-Aft Bending Vibrational Mode

When asymmetric wind loadings are present, there is also an additional effect which can be created on the turbine tower. The unbalance of forces on the rotor can in turn cause bending vibrations in the tower to occur in the front to back direction (fore-aft). If left unchecked, this bending could potentially cause large material fatigue in the tower structure and possibly lead to damage. This can be avoided in the same way which the rotor loading was balanced, by modifying blade pitch. The control system takes sensitive measurements of acceleration on the tower top, and uses this to calculate information about the tower bending mode. It then attempts to damp the bending vibrations by appropriately pitching a turbine blade, creating an equal but opposite disturbance to the tower.

3.6.4 Generator Torque Control

As described in the independent blade pitch control section, it is the goal to maintain a constant generator shaft speed when winds are in performance region 3. In these situations, it is also desirable to maintain constant generator torque, in order to keep power output constant. This then becomes the primary task of the generator torque control system, to minimize torque fluctuations as much as possible. At the same time, these variations in torque can also excite vibrational modes in the towers side to side bending as well as in the rotation, or torsion, of the drive train. Again, by actually adding very small perturbations to the generator torque, it has been shown that active damping can be added to the side-side bending of the tower, as well as the torsion of the generator drive train.

3.6.5 First Side-Side Bending Vibrational Mode

As show previously, unbalanced forces can result in vibrational modes of the turbine tower being excited. In a very similar situation, an unbalance of torques in the drive train system can cause side to side bending vibrations in the tower. Again, such disturbances can cause large material fatigues in the support tower, and potentially lead to damage. Fortunately, these vibrations can also be damped by a controlled response in the generator torque control system. By intentionally applying small increases or decreases to the generator torque, a canceling effect is created, effectively damping bending vibrations in the towers side-side direction.

3.6.7 First Drive Train Torsional Mode

The concept of torsional vibrations may seem slightly foreign when compared to the more common bending vibration. However, they are in fact related. In the case of bending vibrations, the displacement of the object occurs as translational motion perpendicular to the objects axis. Torsion refers to the case in which the applied torque to a body causes rotational motion around the objects axis. So in this case of torsional vibration, oscillating angular displacements of the drive train occur, which of course create significant stresses and fatigue. The control scheme again attempts to damp out these vibrations by applying small variations in the drive train torque at the appropriate times.

3.7 Energy Storage

One of the largest drawbacks of using renewable energy sources like wind and solar power remains the intermittency. For solar, power can only be generated during the day. With wind power, the wind is not always reliable and periods of strong wind activity could be followed by a span with little wind. Wind availability also changes seasonally and can be affected also by storm systems and large scale weather patterns. To combat this, scientists and engineers are researching ways of efficiently storing excess energy during times of high energy production so that it can be used as a backup power source when energy production is low and keep the flow of electricity at a fixed level as it is needed.

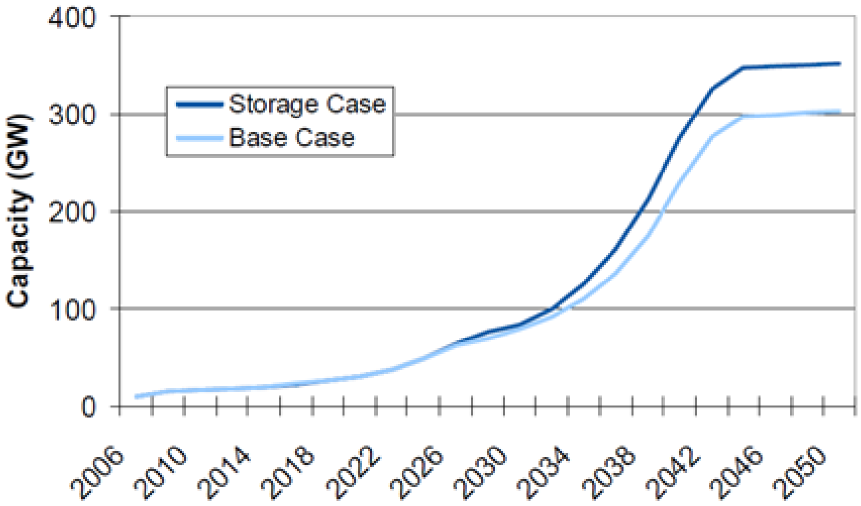
Currently, power grid system operators always maintain operating reserves, which is essentially spare capacity that normally does not get used. These reserves are typically equal to 5-7% of total generation at any given time (41). These reserves are more or less for emergency situations when there are rapid and unpredictable changes in electrical production or demand. For example they are needed when a large power plant unexpectedly shuts down and there is a large instantaneous change in electricity supply. To allow the flexibility to respond to a variety of unexpected problems, grid operators often pool reserves for the entire system so that they can be utilized in any location. This reserve system can consist of spinning or non-spinning reserves. A spinning reserve is typically a power plant that operates below its maximum output level so that the output can be rapidly increased to meet demand. A Non-spinning reserve is an inactive power plant that can start up if needed in a relatively short amount of time, typically between 10-30 minutes (41).

Usually, changes in the total energy output from wind turbines spread over a reasonably large area tend to occur rather slowly. Also, when wind farms are built over large areas, the variability within the area itself can help to level out the overall power output. For example, when it is very windy in one area it may make up for the low wind on the other side of the farm. This is very helpful because it allows the operator some lead time to make a prediction or forecast of the future wind patterns. Nevertheless, regardless of how accurately one can predict the behavior of the wind, the current infrastructure does not allow operators to dispatch wind power as it is needed to meet demand in the same way they can with a conventional power plant (42). Effectively storing excess wind energy would improve the efficiency of energy production as well as allow for a greater percentage of overall power to be produced from wind. The main ideas behind energy storage are to make sure that energy isn’t wasted and to make energy production more efficient by removing some of the burden of spinning and non-spinning reserves, which would otherwise operate inefficiently, having to ramp up and down their outputs to compensate for supply and demand variations. Today, most types of energy storage are too expensive and/or unproven to be operated commercially alongside wind turbines. However, there is sufficient information about some types of storage that can be used to predict their feasibility.

Currently, the U.S. Department of Energy has high hopes for the potential of wind energy. The DOE recently released a technical report that outlines a plan for 20% of America's electricity demand to be met by wind power by the year 2030. To assess the value that energy storage technologies could add to wind, researchers from the National Renewable Energy Laboratory performed a study called "Modeling the Benefits of Storage Technologies to Wind Power." The model known as the Regional Energy Deployment System was used for the analysis of storage and non-storage scenarios in a "business-as-usual" case and a "20% wind energy by 2030" case. For this model, three kinds of energy storage technologies were analyzed. The storage options available were pumped hydro storage (PHS), compressed air energy storage (CAES), and battery systems. For this study the battery was assumed sodium-sulfur as it is a well established technology (42). PHS works by pumping water from a lower to higher elevation reservoir using excess generation capacity. When demand is higher, the plant operator can release water from the high elevation reservoir and use it to generate electricity through a turbine like a traditional hydro plant. CAES is a type of hybrid technology that uses excess production to run large air compressors which are fed into underground caverns. When needed, the compressed air is released and used to run gas turbines. These energy storage methods are sufficient for this analysis, but are not the only options. Other storage types in development that are further from being commercially viable will be discussed later in the project.

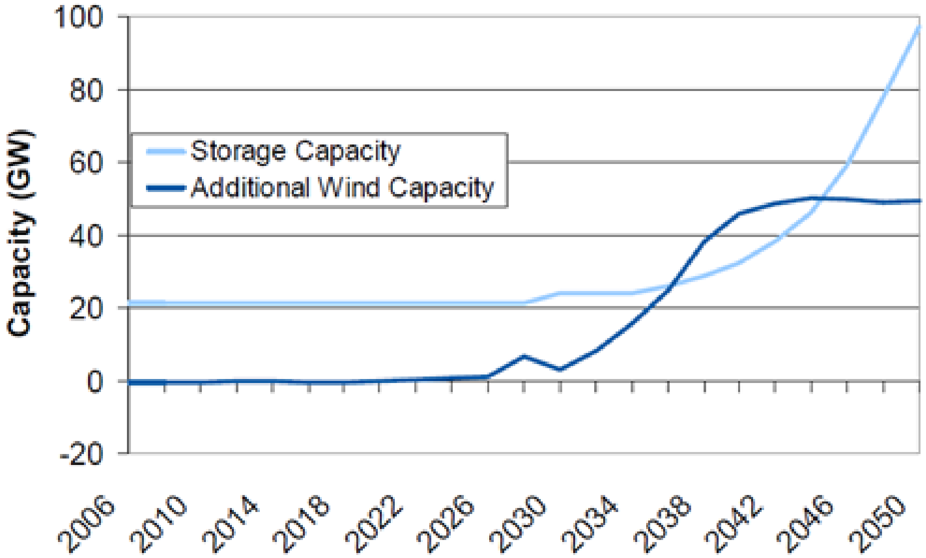
The projections from the storage benefits model show that with adequate deployment of storage, there could be nearly 50 more GW of wind capacity for the same amount of wind base, and the price of energy from wind could be 3 dollars less per MWh by the year 2050.

Figure 50: Cumulative Wind Capacity Comparison, Business-as-Usual Case (42)



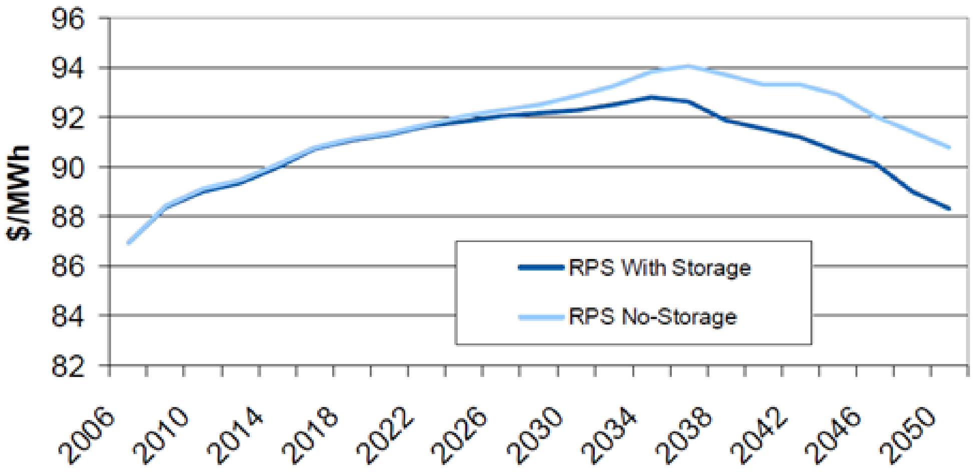
The graph above shows that even in the business-as-usual case, wind capacity with storage is close to 350 GW in 2050 as opposed to 300 without storage.

Figure 51: Effect of Storage on Wind Capacity, Business-as-Usual Case (42)



The graph above shows that storage capacity has the potential to grow almost exponentially even as the additional wind capacity remains relatively constant.

Figure 52: Electricity Price Comparison, 20% Wind by 2030 Case (42)



The graph above shows electricity price comparisons for the 20% wind energy by 2030 scenario and the price per MWh with storage is around 3% less than the price without. Based on this, the price of electricity will drop down almost to current prices by 2050.

The above data is consistent with normal electricity prices between 8.5 – 9.5 cents per kilowatt-hour for both the storage and non-storage scenarios. The data that was compiled shows that energy storage systems can be beneficial in the long run. Storage reduces the need for spinning reserves and it allows for greater utilization of the variable output from wind energy.

Fuel cells are one type of storage that is still in development, but could one day be the solution to the energy storage problem. The idea behind hydrogen fuel cell storage is that the wind-generated electricity is passed through water to split it into hydrogen and oxygen. Then, the hydrogen can be stored and used later to generate electricity, or the hydrogen could be stored and used to refuel hydrogen fuel cell powered cars (44). Another storage option is the use of inertial flywheels. The plant would store excess electricity from non-peak times in 2,500-pound flywheels that turn faster than the speed of sound. When the electricity demand rises, or when winds die, energy can be withdrawn from the wheels and sold back to the grid at a premium rate

(43). Storage becomes more necessary as a greater proportion of electricity is generated from wind power. Successfully storing and reusing excess energy from wind systems is crucial to the growth and advancement of wind power in America.

3.8 Turbine Noise

Wind turbine noise disturbance is one of the major barriers on the local scale to constructing new wind farms. Turbine noise is generated both mechanically and aerodynamically. The level of sound that a turbine generates is an important factor in choosing the site where the turbine is to be built. In order to study and understand the sound generated by wind turbines one must first define noise and sound.

Sound is generated by small pressure fluctuations and is transmitted as vibrations through some medium, in this case air, which produce sensations in the human ear. Noise differs from sound in that noise is unwanted sound. Noise is usually sound which exceeds the ambient background level. Sound waves are characterized in terms of their amplitude or magnitude, wavelength (λ), frequency (f) and velocity (v), where v is found from (45):

$$v = \lambda f$$

The velocity of sound is a function of the medium through which it travels, and it generally travels faster in more dense mediums. The frequency range of human hearing is quite wide, generally ranging from about 20 – 20,000 Hz. (45).

Various measures of the magnitude of sound include sound power level and sound pressure level. Sound power level is the power transmitted per unit area of the sound wave; it is a property of the source of the sound and it represents the total acoustic power emitted by the source. Sound pressure is a property of sound at a given observer location and can be measured there by a single microphone (45)

Sound Intensity, L_I

$$L_I = 10\log_{10} (I/I_0)$$

Where the reference intensity, I_0, is often the threshold of hearing at 1000 Hz: $I_0 = 10^{-12}$ W/m^2.

Sound Power Level, L_w

$$L_w = 10\log_{10} (W/W_0)$$

Where W is equal to the sound power level and W_0 is a reference sound power (often $W_0 = 10^{-12}$ W).

Sound Pressure Level, L_p

$$L_p = 10\log_{10} (p/p_0)$$

Where p is equal to the effective (or root mean square, RMS) sound pressure and p_0 a reference RMS sound pressure (usually $2\text{x}10^{-5}$ Pa).

As was mentioned earlier, turbines can produce sound mechanically or aerodynamically. Mechanical sounds originate from motion and vibration within the moving parts of the turbine such as cooling fans, hydraulics, the gearbox, generators and yaw drives. Aerodynamic sound, which is usually the largest component of turbine noise emissions, originates from the contact of air with the blades (45).

Noise disruption is more of an issue with small residential turbines than it is with large commercial turbines for several reasons. Turbines in residential areas are in closer proximity to homes than are large wind farms, thus their effect on residents must be measured before sites for turbines are approved. Small wind turbines may also operate at higher tip speeds or turned partially out of the wind (this is known as furling, and is a common power limiting mechanism for high winds). The process of furling can produce loud aerodynamic sound. Sound from small turbines (under 30kw capacity), as opposed to larger ones, is generated mostly aerodynamically while mechanical noises are small in comparison due to fewer moving parts in smaller turbines (45).

Over time, the overall sound level produced by wind turbines has been reduced as the technology has improved. Blade airfoils have become more efficient; meaning more of the wind energy is converted into rotational energy as opposed to acoustic energy. Vibration damping and improved mechanical design have also significantly reduced noise from mechanical sources. The use of high gearing ratios also enables the blades to turn slower, also resulting in reduced aerodynamic noise. Nevertheless, turbines still produce enough sound to potentially disrupt and annoy people living in close proximity. Effects from turbine noise can be a small nuisance or annoyance, or they can be more serious, interfering with peoples' daily lives. The actual amount of noise from a turbine which is heard by a person nearby is based on many factors (45).

- Source characteristics (output sound level, directional distribution, height, etc.)
- Distance of the source from the observer
- Air absorption, which depends on frequency
- Ground effects (i.e. reflection and absorption of sound on the ground; dependent on source height, terrain cover, ground properties, frequency)
- Shape of the land (certain land forms can focus or muffle sound)
- Blocking of sound by obstructions and uneven terrain
- Weather effects (i.e. wind speed, wind direction, change of wind speed or temperature with height).

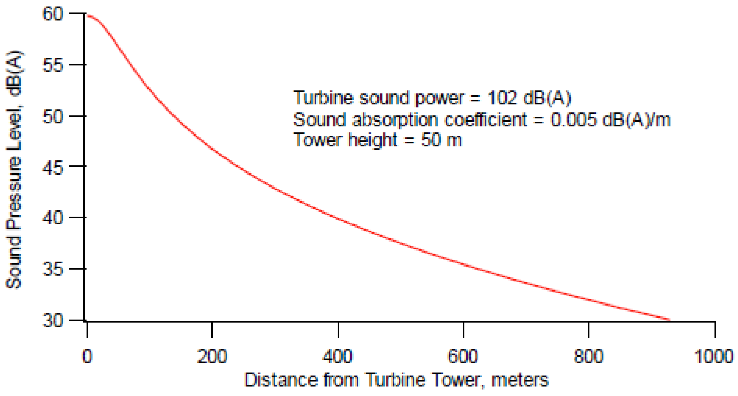
In order to approximate the sound level from a turbine at a give distance away, a simple model based on the conservative assumption of hemispherical sound propagation over a reflective surface is often used (46):

$$L_p = L_w - 10\log_{10}(2\pi R^2) - \alpha R$$

Here L_p is the sound pressure level (in dB) a distance R from a sound source radiating at a power level Lw (dB). α is the frequency-dependent sound absorption coefficient. The total sound produced by multiple wind turbines would be calculated by summing the sound levels due to each turbine at a specific location using the dB math mentioned above.

The following graph is an example of the sound level vs. distance for a single large turbine. This example assumes hemispherical sound propagation and uses the formula presented above. In this case the wind turbine is assumed to be on a 50 m tower, the source sound power level is 102 dB(A), and the sound pressure level is measured at ground level (45).

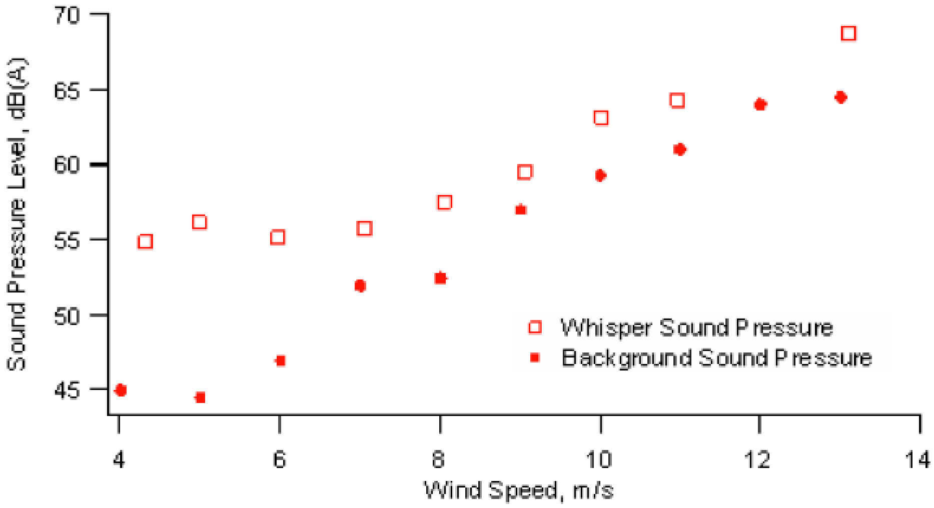
Figure 53: Sound Pressure vs. Distance from Tower (45)



In a real world study, sound measurements were made by the National Renewable Energy Laboratory on a 900 W wind turbine, the Whisper 40. The Whisper 40 wind turbine had a rotor diameter of 2.1 m and was mounted on a 30 ft tower. The rotor rotates at 300 rpm at low power.

The rotation speed increases up to 1200 rpm before the rotor rotates out of the wind (furls) to limit power in high winds. The following figure depicts the measured background noise along with the turbine noise of the Whisper 40 at a distance of 10 meters from the wind turbine base (47).

Figure 54: Sound Pressure vs. Wind Speed (47)



The graph above shows that the Whisper 40 turbine produces sounds between 55-70 dB with wind speeds between 4-14 m/s. These sound levels are appropriate because the sound difference between background and turbine noise is generally less than 10 dB at only 10 meters from the turbine (whereas most residences will be much more than 10 meters away).

For comparison, the following charts show the output sound levels in decibels from several common sources (48), and the measured sound level (emission) at various distances for different turbine output sound levels.

Figure 55: Decibel Levels of Some Common Items (56)

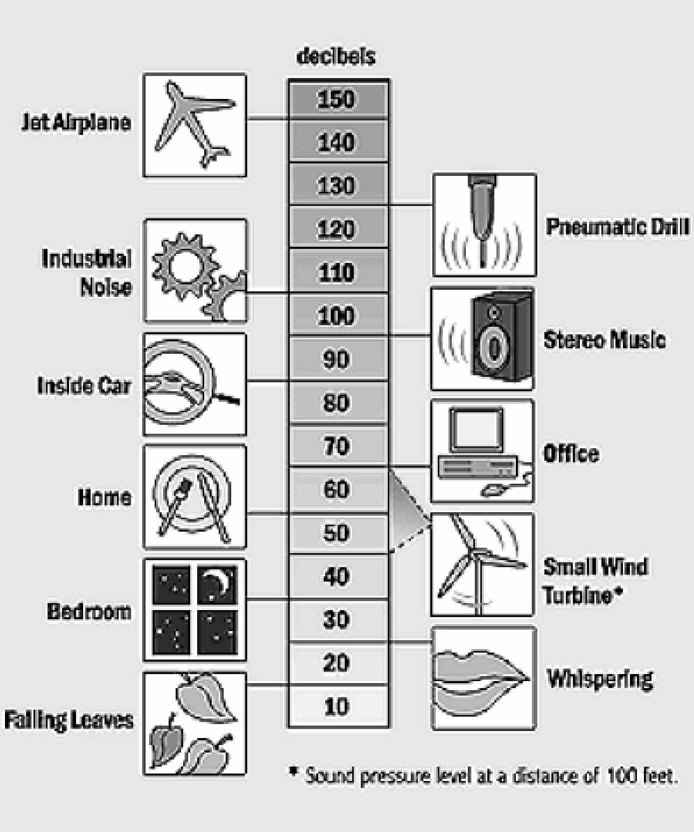


Table 8: Sound Level from Wind Turbines at Various Distances (57)

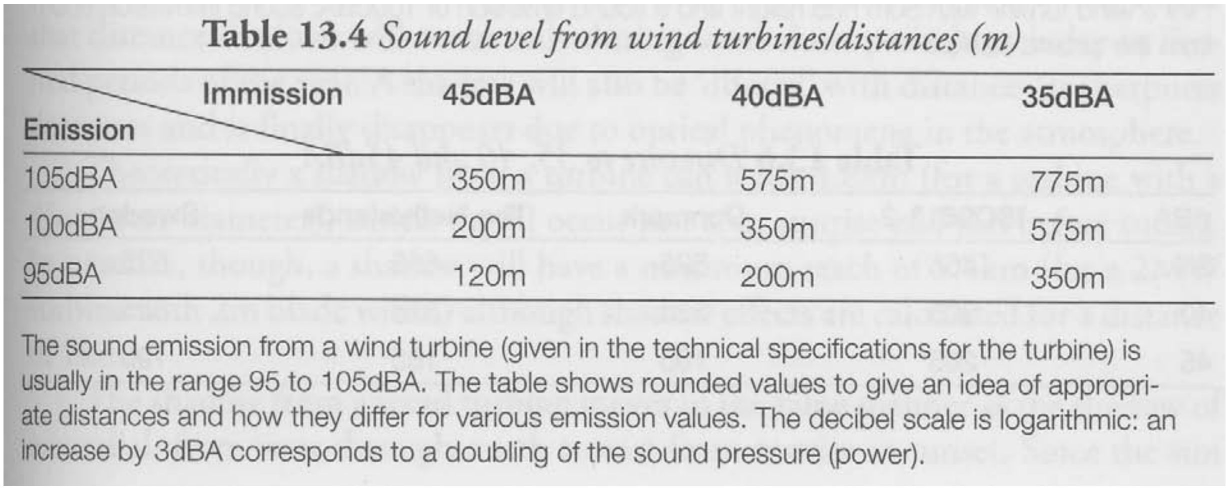


Table 13.4 *Sound level from wind turbines/distances (m)*

Emission \ Immission	45dBA	40dBA	35dBA
105dBA	350m	575m	775m
100dBA	200m	350m	575m
95dBA	120m	200m	350m

The sound emission from a wind turbine (given in the technical specifications for the turbine) is usually in the range 95 to 105dBA. The table shows rounded values to give an idea of appropriate distances and how they differ for various emission values. The decibel scale is logarithmic: an increase by 3dBA corresponds to a doubling of the sound pressure (power).

The ability to hear a wind turbine in a given installation also depends on the ambient sound level. When the background sounds and wind turbine sounds are of the same magnitude, the wind turbine sound gets lost in the background. Ambient baseline sound levels will be a function of such things as traffic, industry, machinery, wind blowing trees and leaves, dogs, birds, children etc. It will vary with time of day, wind speed and direction and the level of human activity.

Both the wind turbine sound level and the ambient sound level are functions of wind speed, so when the turbine sound output is increased due to wind velocity, the background sound level is also increased (45). Some various noise restrictions from various agencies worldwide include (49):

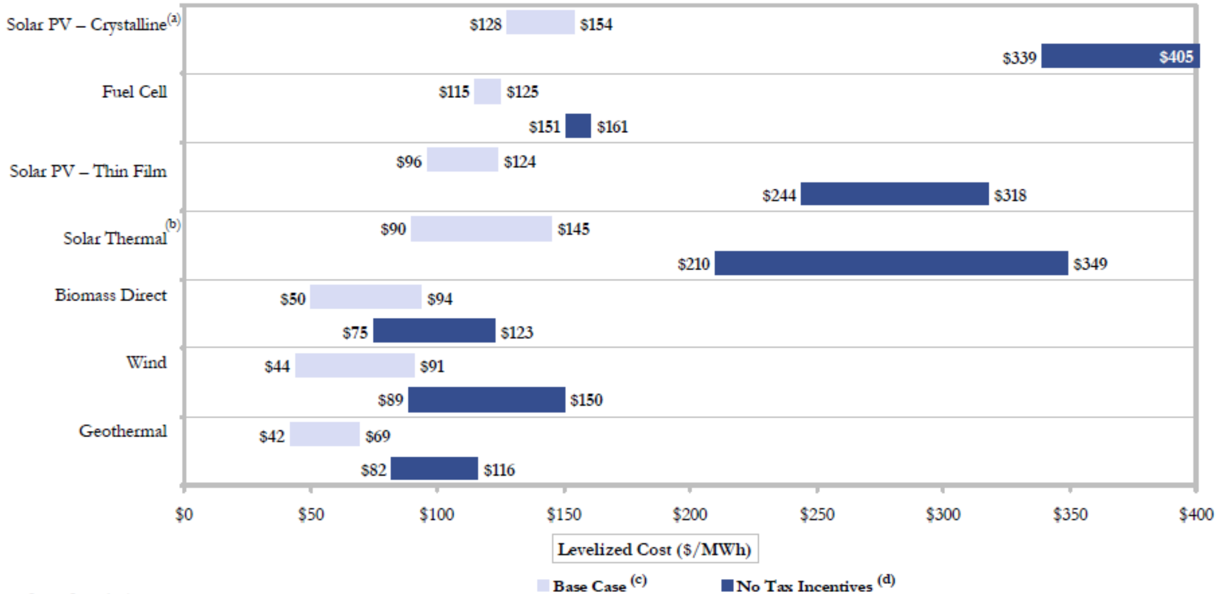
- 49-67 dB for U.S. federal agencies
- 35-45 dB at night in Europe.
- Massachusetts and Oregon limit new broadband (atonal) sounds to 10 dB above ambient.
- The World Health Organization (WHO) sets limits of 55 dB outside during the day, 45 dB outside at night, and 30 dB indoors at night for sleeping.
- The American National Standards Institute (ANSI) limits indoor background noises to 35 dB in classrooms.

In designing a wind turbine project, one of the significant challenges is sitting the project in an area that is far enough from residences and businesses so that noise disruption will be minimal. The magnitude of the emitted sound from turbines and the attenuation of that sound over distance are affected by many factors including turbine design, size, geographical features and weather conditions. When building turbines near residential areas, it is difficult to completely remove all the auditory and visual effects of the turbine; however that should not discourage turbine development. Meeting noise regulation goals is necessary for the development of the wind industry as well as important for the welfare of local communities. The most important way to control how turbine noise affects near-by residents is by performing studies prior to construction and examining the outcome of projects in similar geographical situations.

3.9 Economics and Competitiveness

The ultimate factor that will determine what impact wind energy will have in supplying the world with energy is the cost. Currently the cost of energy generated by wind turbines is more expensive than energy generated from fossil fuel sources. The costs of wind energy are much more competitive, however, when two things are introduced, wind farm subsidies and carbon emission costs. Subsidies are government incentives in which the government will cover some of the costs of the wind farm construction to make them more affordable. Carbon emission costs are taxes put on carbon dioxide emissions which increase the ultimate price of energy from oil, coal and natural gas sources. The following graphs and tables attempt to show true costs of energy for renewable and traditional sources, looking at such things as capitol costs, operations and maintenance, tax incentives, carbon emission prices and energy provided. In all of these analyses, certain assumptions are made regarding things such as payback period, economic life and interest rates, and are describes as applicable below each figure.

Figure 56: Cost of Renewable Energy Technologies (50)

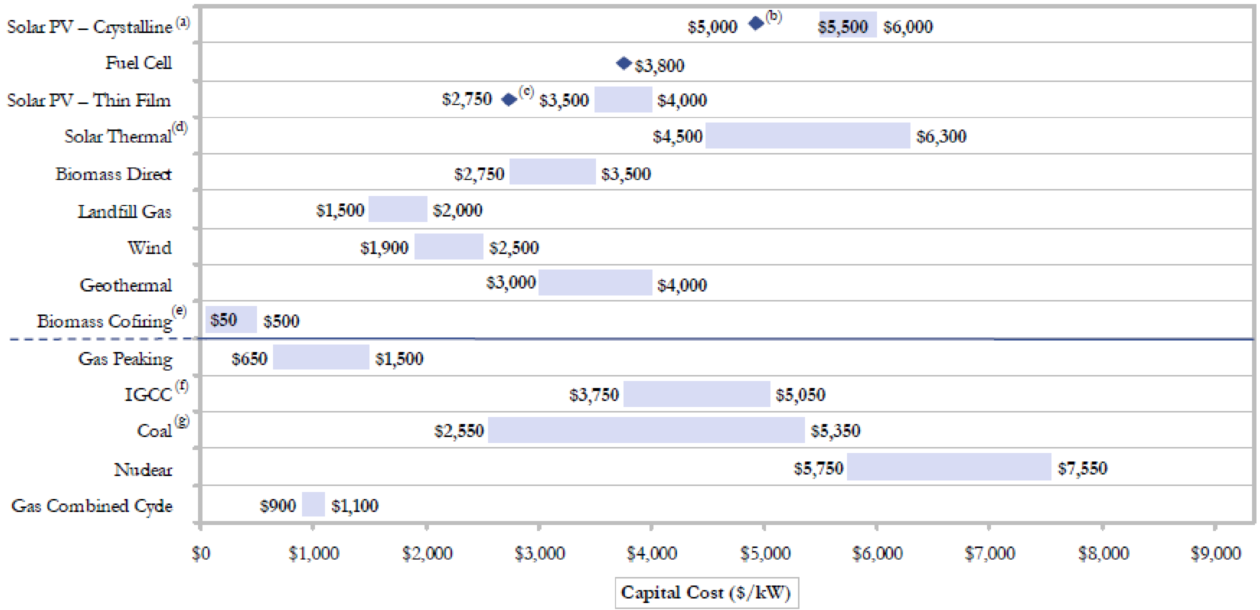


Source: Lazard estimates.

Note: Assumes 2008 dollars, 60% debt at 7% interest rate, 40% equity at 12% cost, 20-year economic life and 40% tax rate. Assumes coal price of $2.50 per MMBtu and natural gas price of $8.00 per MMBtu.

(a) Low end represents single-axis tracking crystalline. High end represents fixed installation.
(b) Low end represents solar tower. High end represents solar trough.
(c) Reflects production tax credit, investment tax credit, and accelerated asset depreciation as applicable.
(d) Illustrates levelized cost of energy in the absence of U.S. federal tax incentives such as investment tax credits, production tax credits and assuming 20-year tax life.

Figure 57: Capitol Cost Comparison (50)

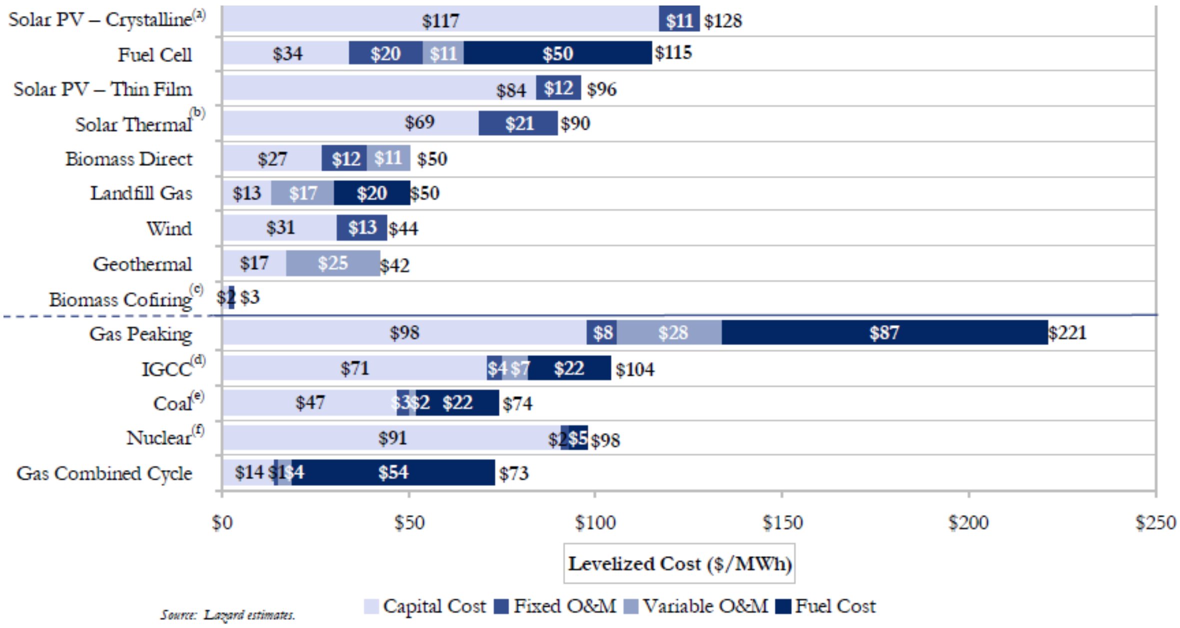


Source: Lazard estimates.

(a) Low end represents single-axis tracking crystalline. High end represents fixed installation.
(b) Based on a leading solar crystalline company's guidance of 2010 total system cost of $5.00 per watt. Company guidance for 2012 total system cost is $4.00 per watt.
(c) Based on the leading thin-film company's guidance of 2010 total system cost of $2.75 per watt; company guidance for 2012 total system cost is $2.00 per watt.
(d) Low end represents solar trough. High end represents solar tower.
(e) Represents retrofit cost of coal plant.
(f) High end incorporates 90% carbon capture and compression.
(g) Based on advanced supercritical pulverized coal. High end incorporates 90% carbon capture and compression.

IGCC: Integrated Gasification Combined Cycle

Figure 58: Levelized Cost of Energy Production - Low End (50)

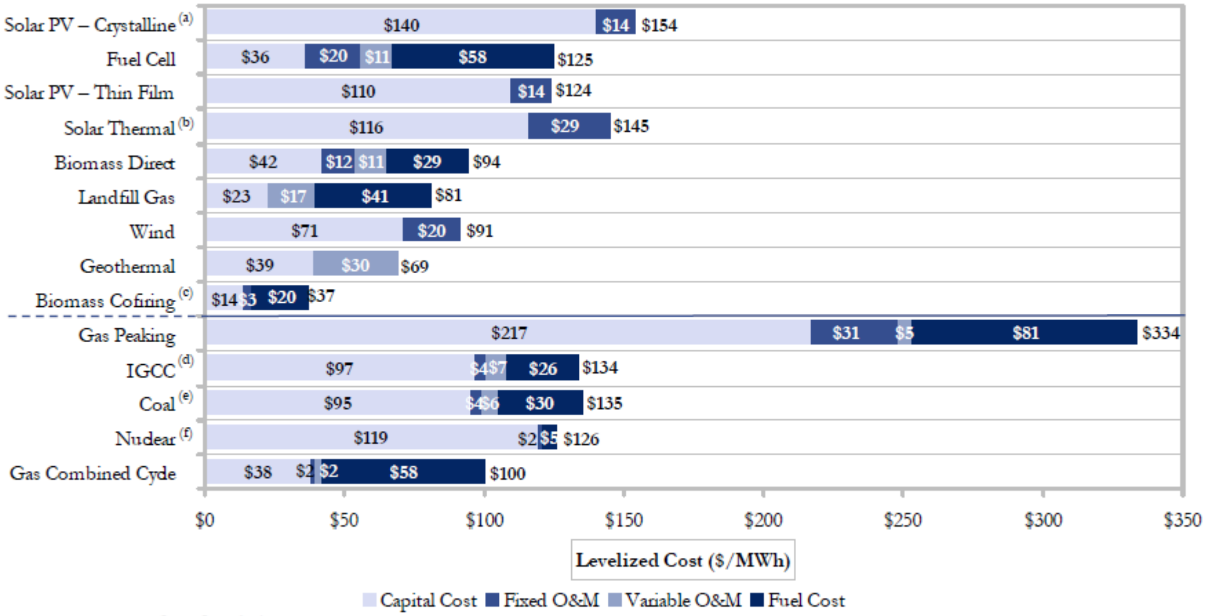


Source: Lazard estimates.

Note: Reflects production tax credit, investment tax credit, and accelerated asset depreciation as applicable. Assumes 2008 dollars, 60% debt at 7% interest rate, 40% equity at 12% cost, 20-year economic life, 40% tax rate, and 5-20 year tax life. Assumes coal price of $2.50 per MMBtu and natural gas price of $8.00 per MMBtu.

(a) Low end represents single-axis tracking crystalline. High end represents fixed installation.
(b) Low end represents solar tower. High end represents solar trough.
(c) Represents retrofit cost of coal plant.
(d) Incorporates no carbon capture and compression.
(e) Based on advanced supercritical pulverized coal. Incorporates no carbon capture and compression.
(f) Does not reflect potential economic impact of federal loan guarantees or other subsidies.

Figure 59: Levelized Cost of Energy Components - High End (50)



Source: Lazard estimates.

Note: Reflects production tax credit, investment tax credit, and accelerated asset depreciation as applicable. Assumes 2008 dollars, 60% debt at 7% interest rate, 40% equity at 12% cost, 20-year economic life, 40% tax rate, and 5-20 year tax life. Assumes coal price of $2.50 per MMBtu and natural gas price of $8.00 per MMBtu.

(a) Low end represents single-axis tracking crystalline. High end represents fixed installation.
(b) Low end represents solar tower. High end represents solar trough.
(c) Represents retrofit cost of coal plant.
(d) Incorporates 90% carbon capture and compression.
(e) Based on advanced supercritical pulverized coal. Incorporates 90% carbon capture and compression.
(f) Does not reflect potential economic impact of federal loan guarantees or other subsidies.

Figure 60: Total Wind Energy Costs, 1987-2006 (51)

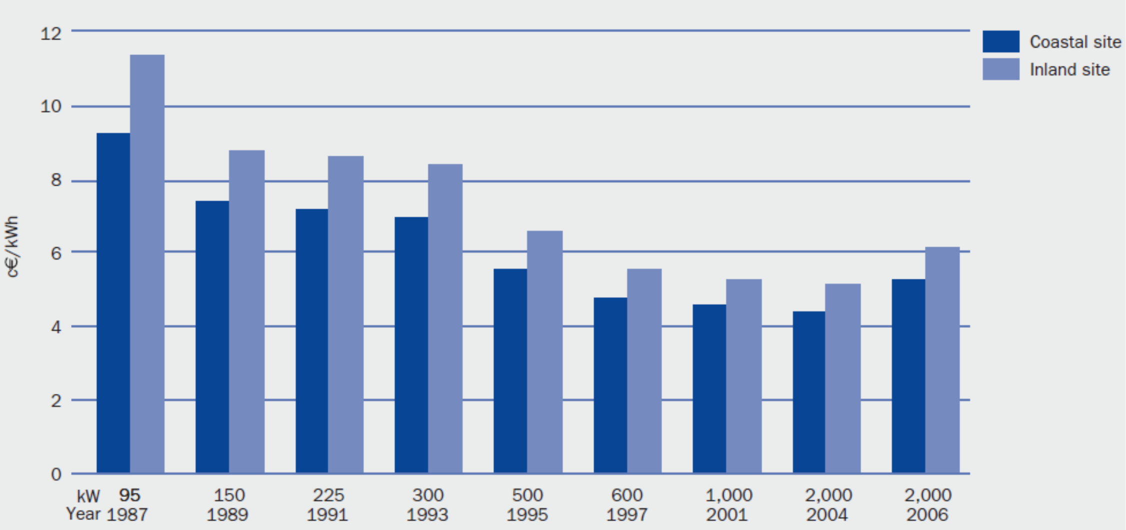
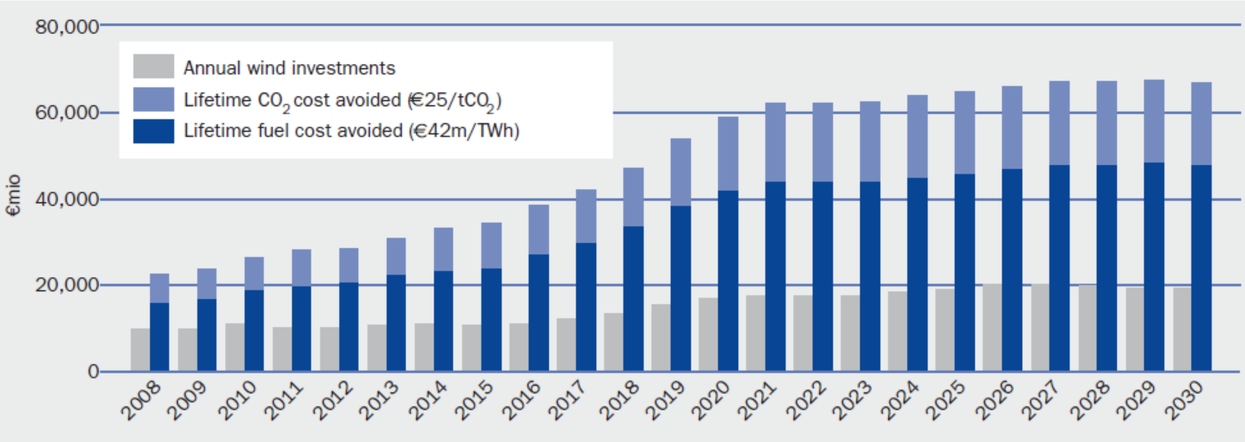


Figure 61: Wind Investment vs. Lifetime Avoided Costs (51)



These figures and estimates show that wind and other renewables are already feasible options when tax credits and carbon costs are taken into account. From the graphs, one can see that the price and efficiency of wind turbines is nearing a limit. Costs of traditional energy generation and wind generation have leveled out, and when all the factors are considered all are feasible options economically.

3.10 Small Scale Wind Potential

“Many more people would buy small wind systems if they were cheaper. But, we can’t make them cheaper unless many more people buy them.”
-David Blittersdorf, President, AWEA

Small scale turbines were mentioned several times earlier when talking about noise distribution as well as low speed turbines. Residential turbines can be effective energy generators; however, their history has not been as successful as their larger relatives. Large-scale wind turbines and farms have proven that they can be effective sources of affordable clean energy, but what about small turbines? Can small turbines at residential and business sites be as effective as large turbines and can they be economically feasible options for the average American? Small wind systems (100 KW or less) can either be connected to the grid or they can be connected to a battery and used for backup power (53). Being connected to the grid allows the turbine owner to use electricity from the local utility when the turbine doesn’t produce enough power. In addition, any energy produced in excess of consumption can be sent back to the grid for financial credit to the owner. Small wind systems however are not ideal for every home and business. There are several important criteria that should be met in order for a small wind turbine to be considered:

- There must be adequate space for a turbine on the property or on a roof top; turbine sites are usually at least 0.5 acres (54).

- There should be enough room between the turbine and neighboring properties so that there is minimal audio and visual interference.

- The local zoning allows wind turbines in residential areas.

- The property should have good wind resources, with few tall trees or other structures that could block some of the gusts.

Most small wind turbines greater than 1 KW are grid connected in the US (53), as there are several advantages to a grid-connected system. In order for a grid system to be economically realistic though, several factors should be considered:

- Small wind systems are most effective in areas where electricity prices are relatively high (10-15 cents/KWh) (54)
- The costs of connecting to the grid can be substantial and increase depending on the distance away from the nearest grid point.
- Systems are most affordable when there are strong financial incentives for the sale of excess electricity back to the grid, as well as for the purchase and installation of wind turbines.

An off-grid system is also a viable option for small wind systems, usually in the form of hybrid systems. A hybrid system is one that combines wind and photovoltaic technologies. The benefit to having a hybrid system is a more consistent electric output throughout the year. The sun shines brightest and longest during the summer, however that is also when winds speeds are lowest. In the winter, less sunlight is available, however, the wind is strongest. An off-grid system must also be connected to a battery and/or generator so that sufficient energy can be produced when neither the wind turbine nor the PV modules are providing power (54).

The largest drawback to small wind systems may be their ineffectiveness when compared to large ones. The wind power equation shows that the most important factor is wind speed, due to the cubic dependence. Thus, larger turbines can harness the stronger winds available at higher altitudes and can have larger rotors to capture more energy.

Power Output = $\eta \frac{1}{2} \rho A V^3$

η = Maximum Power Coefficient (Usual Range 0.25-0.45)

ρ = Air Density

A = Rotor Swept Area ($\pi D^2 / 4$)

D = Rotor Diameter

V = Wind Speed

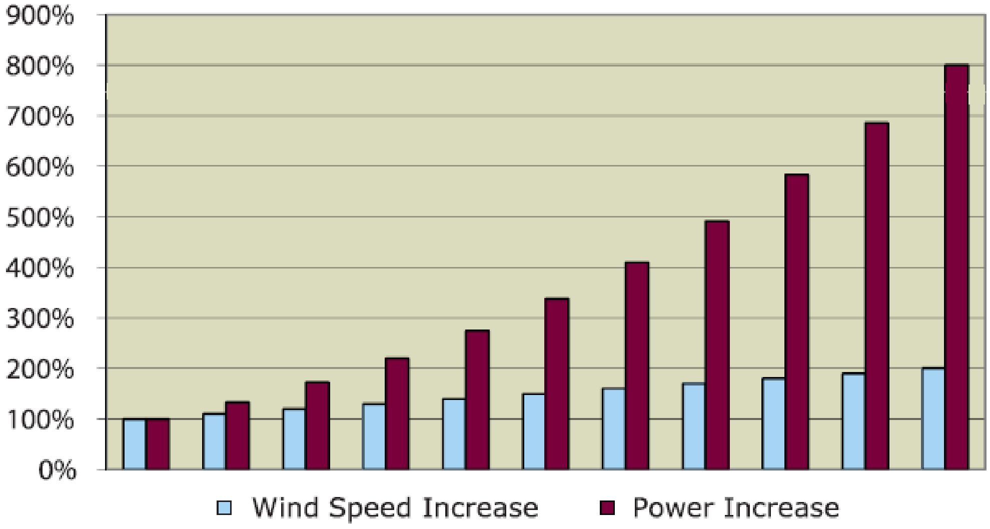
This reality is clearly demonstrated in the following comparison for a 10kW residential-scale turbine (53):

Table 9: Wind Turbine Statistics (53)

Tower height (feet)	Wind speed (mph)	kWh/year	System cost	Incremental cost from 60′	Incremental energy output from 60′	Incremental energy ÷ incremental cost = ROI*
60	7.3	2,709	$48,665	---	---	---
80	9.3	6,136	$49,841	$1176 or 2.4%	226%	226% ÷ 2.4% = 94 to 1 ROI
100	10.7	9,338	$51,346	$2681 or 5.5%	344%	344% ÷ 5.5% = 63 to 1 ROI

*ROI = Return on Investment

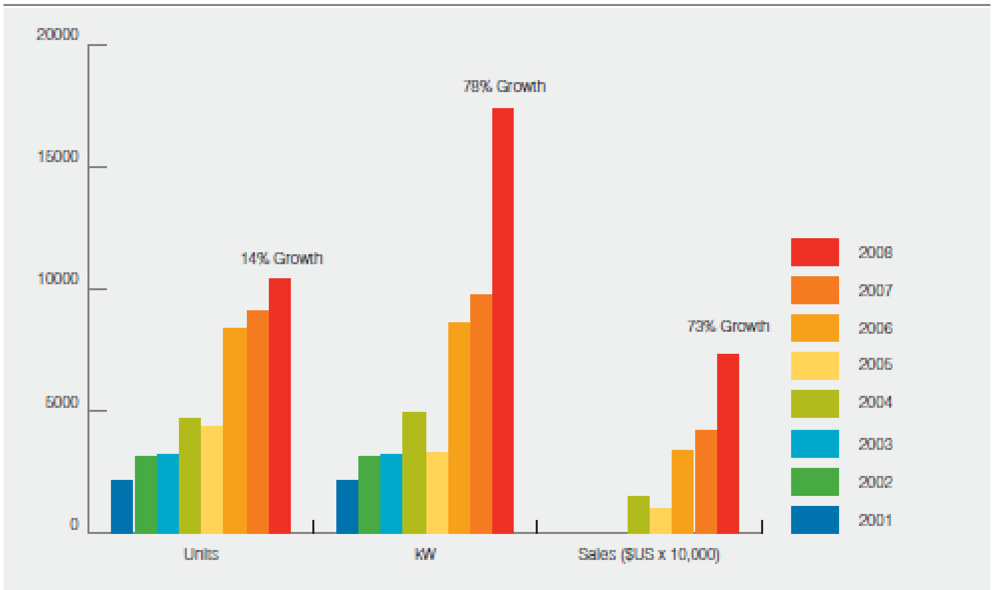
Figure 62: Power vs. Wind Speed (53)



The previous chart and graph illustrate the point that larger turbines at higher altitudes produce energy more efficiently. Although large scale wind systems cost more than smaller systems initially in terms of production and installation, they will show a larger return on the investment over time.

Despite its downfalls, small scale wind can still play an important role as an energy provider in the U.S. In 2008 alone, the U.S. small wind market grew by 78 percent (55).

Figure 63: 2008 Small Wind Growth (55)



SMALL WIND TURBINE GLOBAL MARKET STUDY: 2009

Table 10: 2008 Small Wind Growth by Market Segment (55)

US: Units, 2008	0-0.9kW	1-10kW	11-20kW	21-100kW	Totals
Off-Grid	6,706	696	0	0	7,402
On-Grid	0	2,825	72	87	2,984
Totals	6,706	3,521	72	87	10,386

According to the Organization of American States' Office for Sustainable Development, the average American household uses about 10,000 kWh yearly. And a 10kW turbine at a site with an average annual wind speed of 10 mph produces about 7,700 kWh per year (43). For someone who has the appropriate amount of land (at least 0.5 acres) and the appropriate average wind speeds (at least 10 mph), a single small wind turbine could provide close to 75 percent of their energy need. According to the Department of Energy, the average electricity price for all sectors in the U.S. is 10.73 cents/KWh. Based on that price; a wind turbine could save the average family $800 off of their electricity bill annually. However, to break even within say 15 years would require a full installation cost of under $12,000 to the consumer, an amount far less than the real cost of such a system. At an average installed cost of $3,500/kWatt (52), such a system would total at least $3,500 over its lifetime, leaving the owner with $23,000 in losses after 15 years. From this, it is clear that in order to at least break even, the owner would need access to some type of government rebate or incentive program. Incentives for wind energy will be further discussed in later sections.

3.10.1 Localized vs. Centralized Turbines

Small wind systems have proven that in the right situation they can be a reliable and affordable source of energy, however, how do they compare to much larger systems? A large wind farm consisting of dozens of turbines and a single residential turbine can both be cost effective renewable energy providers, and which system is better depends on many factors, most importantly the needs of the consumer.

Benefits of Large System:

- Can be built away from residential areas so as not to cause noise and visual disturbance.
- Can generate large volumes of electricity, enough to power entire cities.
- Can save money buying materials and constructing in bulk.
- Many turbines can help to balance the performance of the farm; when one area is experiencing low wind speeds another area close by could be at maximum performance.

Benefits of Small System:

- Relatively easy to install, minimal operations and maintenance costs.
- Easier to connect to grid than large farms.
- Can operate off of the grid providing power directly to a generator.

Problems with Large Systems:

- Large costs in interconnection and grid connection.
- Need to build roads and transmission lines to reach farms that are in isolated areas.
- Requires several staff members to be working at all times monitoring and repairing the turbines.

Problems with Small Systems:

- Can cause noise and visual disturbances in residential areas.
- Limited by how much the wind is blowing in one specific spot.
- Size of turbine limited by space.

In the end, large wind farms can probably provide energy at a lower cost to the consumer based on the large volume of energy that they can generate. Nevertheless, both large and small wind systems can be commercially viable, and they both should be used, depending on the situation, whenever possible to provide clean and reliable energy.

Section 4: Wind Energy Outlook

4.1 Energy Vision

Throughout history, it seems it is often the case that humans surprise themselves with their own innovation. This has held quite true in the world of energy in particular. Twenty-five years ago, the idea of wind energy likely seemed relegated to always being only a niche market; providing power in remote areas where electricity couldn't be transported. The idea of massive wind farms with row upon row of colossal turbines, towering hundreds of feet into the air and stretching for miles in each direction probably seemed like something out of a sci-fi film. However, this dream of the past is indeed now quite real in hundreds of locations across the heartland of America. The question then becomes: what innovations will transform our world in the next 25 years? This answer is obviously still elusive to even the most knowledgeable experts in the energy field. Despite this uncertainty, though, we should still set our ambitions high.

The idea of a completely renewable based society is one receiving ever greater thought in our fossil fuel dependent world. Although it may even be beyond our current "wildest dreams", it is not necessarily futile to plan for such a scenario. One particular such scenario can be imagined by extrapolating the recent success of wind energy far into the future. In this world, wind energy would provide for virtually all forms of our energy needs. A highly efficient and intelligently controlled electrical network would effortlessly direct power from where it is being produced, to the areas of highest demand. This system would be able to predict wind conditions in near real time, and appropriately dispatch generation capacity to wherever it is needed. Such an intelligent grid would be completely interconnected through the entire nation, allowing a virtually limitless number of paths for power to reach its destination, even in the case of system failures in a particular area.

Not only would wind energy provide all of our electric generation needs, but transportation needs as well. This can be envisioned even today with our fledgling plug-in electric vehicle market. By transferring the energy demanded by transportation from liquid fuels to the electric grid, wind energy would again supply the necessary power.

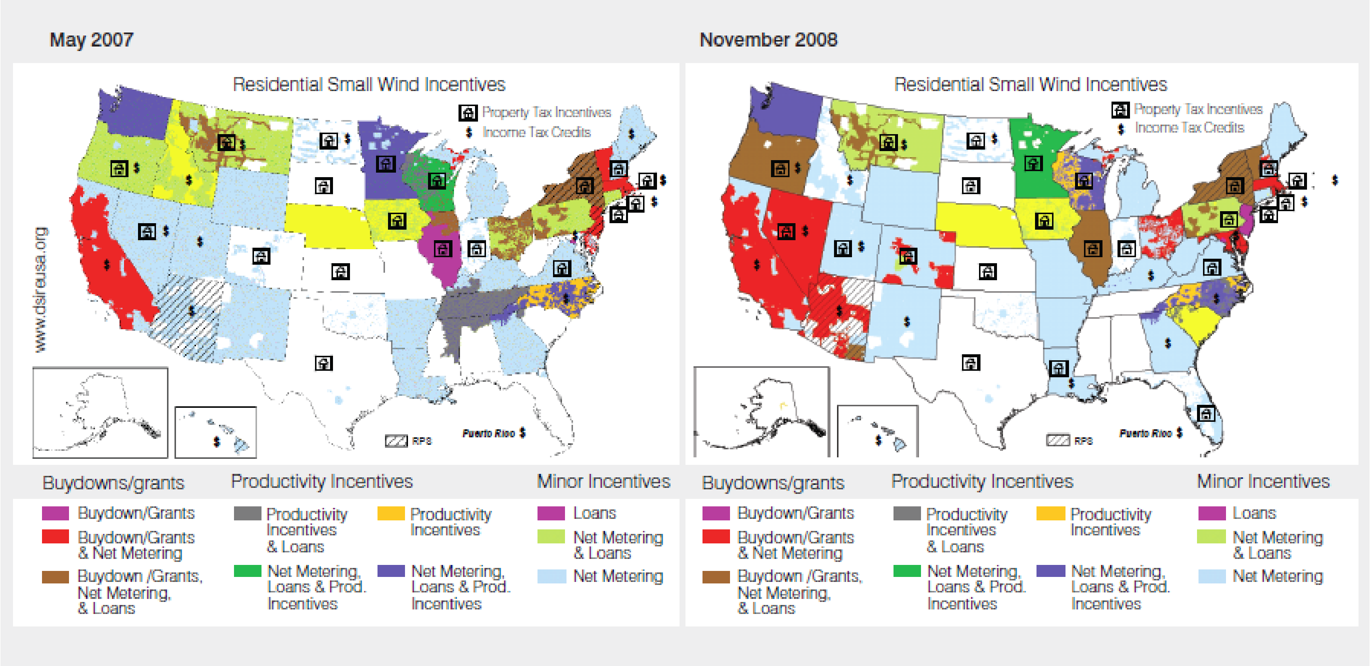
4.2 Policies to Make Wind More Competitive

The main factor that will promote the acceptance of wind energy and renewable energy sources in general is the price of energy. Currently, as was discussed earlier, energy from wind is more expensive than energy from fossil fuels, which is one of the main reasons that such a large percentage of energy generation comes from those sources. Unless renewable energy sources can provide competitive prices to the consumer, then they will never be able provide energy to a significant portion of the U.S. Fortunately, town and state governments, utility companies, and the national government have initiated various programs to promote wind energy by making it more economically competitive.

4.2.1 Tax Incentives

Tax incentives are one way that the federal and some state governments have encouraged the installation of wind turbines. Across the United States, local and state governments, utility companies and non-profit organizations have provided a wide array of financial incentives for investment in, construction and utilization of wind energy. These incentives include but are not limited to: credits in personal, corporate, sales or property taxes, rebates, grants, loans, bonds or production incentives. Usually, states that offer consumer incentives of at least $2,000 per KW of capacity attract the strongest share of the small-wind market. Based on a survey of residential turbine providers, states with highest sales percentages in 2008 were CA, NV, AZ, OR, NY, MA, and OH, all states that offer incentives for small-wind (63). A map of state policies and incentives for wind energy is shown in the following figure.

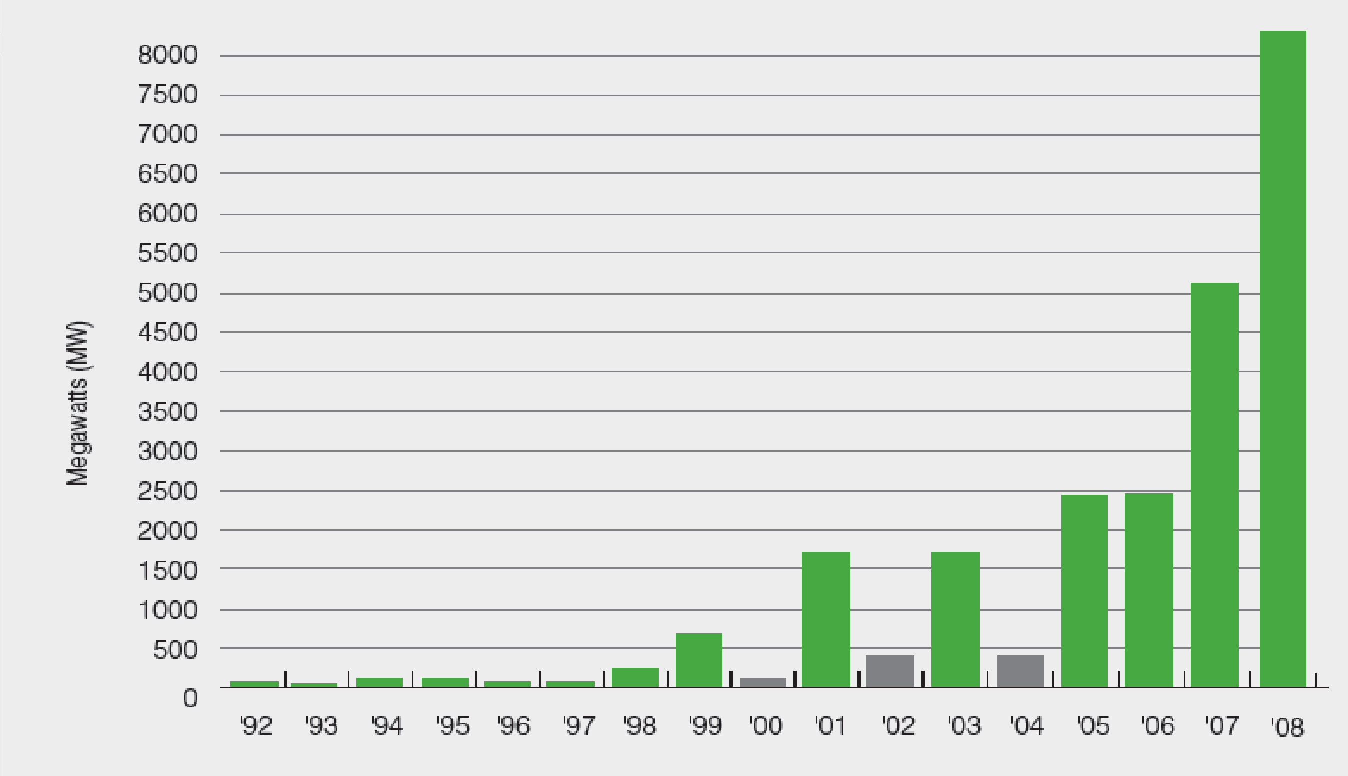
<u>Figure 64: States Policies and Incentives (64):</u>



This figure shows the various policies and incentives offered by many states in the US. These incentives vary widely from grants and loans to productivity incentives and metering. From the maps one can easily see the widespread growth of wind energy from all of the new incentives that were initiated between May 2007 and November 2008.

In addition to local and state governments, the federal government provides many incentives for the development of renewable energy including things like investment tax credits (ITC), production tax credits (PTC), tax deductions, grants, and bonds. Congress passed the Emergency Economic Stabilization Act of 2008, on October 3, 2008, that includes a new eight-year, 30% federal-level investment tax credit (ITC) to help consumers purchase qualified small wind systems with rated capacities of 100 kilowatts (kW) and less. The amount of this credit was stringently capped, however, until the passage of The American Recovery and Reinvestment Act of 2009, on February 17 of that year, which removed the cost caps. A 30% ITC is now available for small wind turbine consumers through December 31, 2016 (65). The American recovery and Reinvestment Act also extended the PTC. In the PTC, companies that generate electricity from wind and several other renewable sources are eligible to receive a 2.1-cent per kilowatt-hour (kWh) benefit for the first ten years of a renewable energy facility's operation. Federal incentives like the ITC and PTC are very important to wind energy and the implementation of these policies directly coincides with increased turbine installation. The following figure shows the annual installed wind power capacity in the US (66).

Figure 65: Annual Installed US Wind Power Capacity (67):



The graph shows steady growth in wind capacity in every year except for 2000, 2002 and 2004. The main reason why there was decreased construction of turbines in those years is due to expiration of the federal production tax credit (PTC) in 1999, 2001 and 2003. The graph is a perfect example of why a long-term federal policy is necessary for the continued success of wind energy.

4.2.2 Portfolio Requirements

Another tool that is important to the success of wind energy is the implementation of a renewable portfolio standard (RPS), also called a renewable electricity standard (RES). A renewable portfolio standard refers to a legal minimum requirement for the percentage of electricity generated by renewable energy sources within a state. Currently in the United States, 29 states and the District of Columbia have a renewable portfolio standard and 6 others have renewable portfolio goals. The following table shows all of the Renewable Portfolio Standards in the U.S. as well as the target year, and the organization administering the standard. The percentages refer to the portion of electricity sales within the state, and megawatts (MW) refer to absolute capacity requirements. Most of these standards are phased in over a period of years, with the date listed referring to when the full requirement takes effect.

Table 11: State Renewable Portfolio Standards (69)

State	Amount	Year	Organization Administering RPS
Arizona	15%	2025	Arizona Corporation Commission
California	33%	2030	California Energy Commission
Colorado	20%	2020	Colorado Public Utilities Commission
Connecticut	23%	2020	Department of Public Utility Control
District of Columbia	20%	2020	DC Public Service Commission
Delaware	20%	2019	Delaware Energy Office
Hawaii	20%	2020	Hawaii Strategic Industries Division
Iowa	105 MW		Iowa Utilities Board
Illinois	25%	2025	Illinois Department of Commerce
Massachusetts	15%	2020	Massachusetts Division of Energy Resources
Maryland	20%	2022	Maryland Public Service Commission
Maine	40%	2017	Maine Public Utilities Commission
Michigan	10%	2015	Michigan Public Service Commission
Minnesota	25%	2025	Minnesota Department of Commerce
Missouri	15%	2021	Missouri Public Service Commission
Montana	15%	2015	Montana Public Service Commission
New Hampshire	23.8%	2025	New Hampshire Office of Energy and Planning
New Jersey	22.5%	2021	New Jersey Board of Public Utilities
New Mexico	20%	2020	New Mexico Public Regulation Commission
Nevada	20%	2015	Public Utilities Commission of Nevada

New York	24%	2013	New York Public Service Commission
North Carolina	12.5%	2021	North Carolina Utilities Commission
North Dakota*	10%	2015	North Dakota Public Service Commission
Oregon	25%	2025	Oregon Energy Office
Pennsylvania	8%	2020	Pennsylvania Public Utility Commission
Rhode Island	16%	2019	Rhode Island Public Utilities Commission
South Dakota*	10%	2015	South Dakota Public Utility Commission
Texas	5,880 MW	2015	Public Utility Commission of Texas
Utah*	20%	2025	Utah Department of Environmental Quality
Vermont*	10%	2013	Vermont Department of Public Service
Virginia*	12%	2022	Virginia Department of Mines, Minerals, and Energy
Washington	15%	2020	Washington Secretary of State
Wisconsin	10%	2015	Public Service Commission of Wisconsin

*Five states, North Dakota, South Dakota, Utah, Virginia, and Vermont, have set voluntary goals for adopting renewable energy instead of portfolio standards with binding targets.

An RPS system places an obligation on electric companies to produce a specific portion of their energy from renewable sources. The RPS relies very much on the private market, because it is a market mandate. An RPS is a very important tool to the success of wind energy because it creates a guaranteed demand for renewable generated power. Many who support the adoption of a RPS believe that it will lead to greater competition and innovation in the energy industry, and deliver energy from renewables at a lower cost, making renewables able to better compete with other energy sources. If it is not feasible for a power company to attain such a portion of energy from renewables, it can purchase tradable renewable energy credits from companies which have an excess. This allows them to then meet the minimum standard.

Many are also pushing for a national RPS, believing that a national standard for all states would benefit everyone. Whether or not the United States adopts a national RPS, renewable portfolio standards can and will help to diversify the sources of our energy, and can help us to get the most out of America's wind potential.

4.2.3 Carbon Emissions

Another possible tool that could help make wind energy more competitive would be to regulate or tax carbon emissions. Because wind turbines produce no carbon dioxide emissions, a carbon cap or tax would help make wind energy more competitive compared to high carbon emitting energy sources like coal and natural gas. A carbon cap is more likely to be established than a carbon tax, as it is difficult to mandate a specific price for the tax that all parties would agree on, and the tax would need to be adjusted often to meet industry demands. Also, with a carbon cap, one can have an idea of the actual amount of reductions that could be achieved before the policy is established. The main goal of a carbon cap is to reduce harmful emissions that contribute to ozone depletion and global warming. However, a carbon cap can also stimulate the development of energy from wind turbines and other renewable energy sources because they would provide an alternative to the purchase of carbon offset credits. When a carbon cap is created, a cap-and-trade system is also established. In a cap-and-trade system, electricity generators have to acquire carbon allowances in order to emit greenhouse gases. Allowances are sold to the entities by the federal government. Entities that require more allowances for increased emissions must purchase them through auction. Entities that receive allowances but do not need them, because they produce little or no carbon dioxide, are allowed to sell their extra allowances at auction to others that do need them. A cap-and-trade system can also indirectly promote renewable energy development, as proceeds from the federal auction could be used to finance incentives for states and utilities to provide for renewable energy generation projects.

Right now, wind energy is the most readily deployable source of carbon-free electricity generation, which is why climate change legislation indirectly promotes electricity generation from wind. Currently in the United States, the American Clean Energy and Security Act is an example of a cap-and-trade bill. This bill was passed in the House of Representatives in June of 2009, and its terms are to reduce carbon dioxide emissions 17% below 2005 levels by 2020 and 83% below 2005 levels by 2050 (70).

4.2.4 Technical Improvements (71)

The key to increasing the efficiency and overall production from wind turbines in the future is continued improvements in the design, construction, and operation of wind turbines in order to ultimately make them more cost effective. There are many components to wind turbines and therefore many possible areas where improved efficiency and design are achievable. Listed below are some areas of improvement that were outlined in a Department of Energy workshop to improve wind turbines:

- Improve efficiency of blades. Current turbine blades are only around 32% efficient; bringing that up to 40-45% would make a turbine much more productive.
- Improve efficiency of alternators. Bringing the efficiency of alternators from 65-80% as it is now, to around 90% would boost turbine performance greatly.
- Increase the swept area of turbines in order to capture more energy per unit.
- Reducing the number of components in a system could simplify design, construction and maintenance of turbines.

- Reducing the overall use of materials in terms of pounds per Watt leads to less expense for materials and construction.
- Improve turbine performance in low-wind conditions as well as in high wind conditions when the turbine kicks off at a certain speed.
- Continue to research and adopt advanced materials that could reduce turbine weight, installation time and cost.
- Develop processes and tools that can more accurately predict the amount of available wind energy so as to put turbines only in optimal locations.
- Improve tower foundations to decrease installation time.
- Develop wireless and other electronic turbine performance monitoring devices that can minimize the frequency of site inspections.
- Continue to develop storage techniques such as batteries and hydrogen storage to maximize the amount of captured energy that can be sold to the grid.

The key to the continued advancement of wind energy is to continually look at past designs and past performance in order to understand where improvements can be made, and to understand what the best and most cost effective methods for design, construction and operation are. Acquiring large sets of data on weather patterns and turbine performance can allow a more complete understanding of wind flow and capture, and can allow for turbines to be built in the most optimal areas.

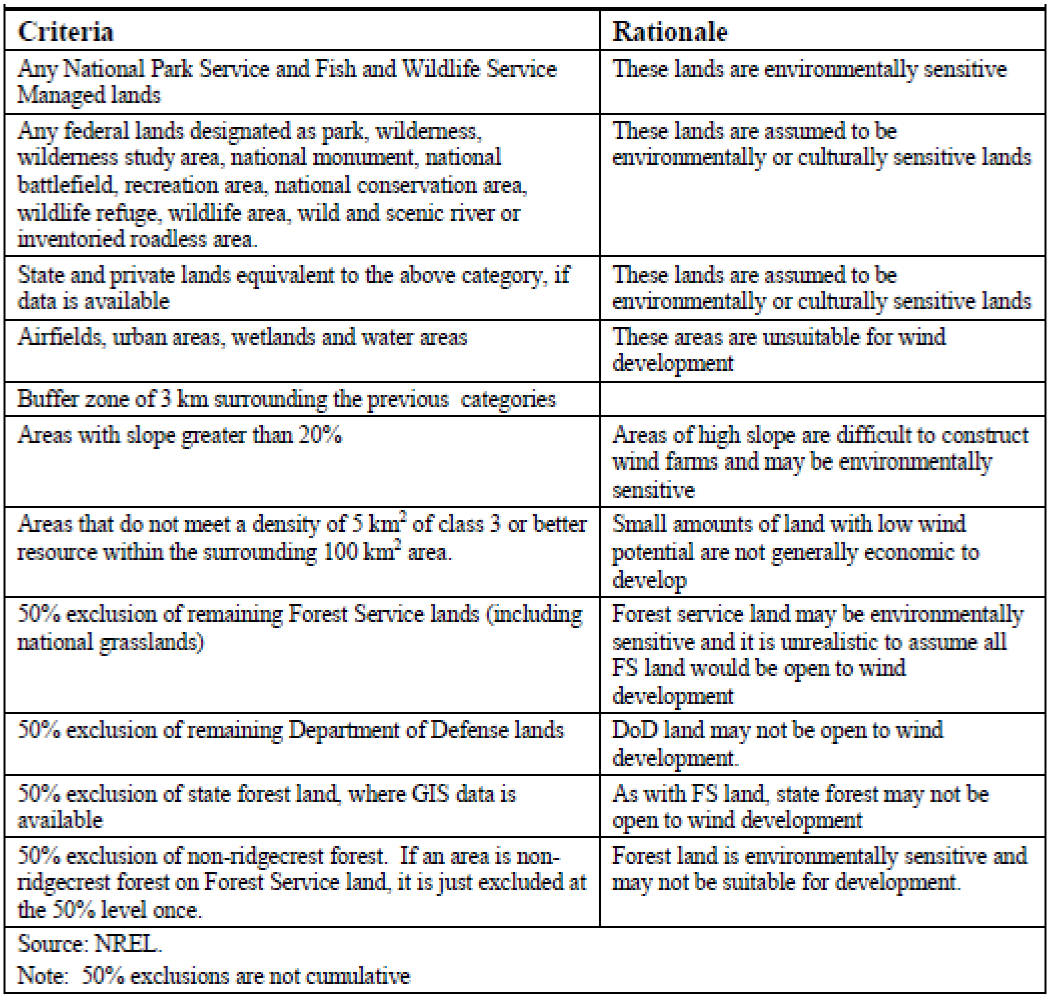
4-3 Wind resource analysis

In order to demonstrate the future potential of wind energy in the US, this section will analyze some of the current estimates of the total wind resource and its availability. This task truly requires a massive scale analysis to produce meaningful, realistic results, and requires years of data gathering from thousands of sources across the nation. The basis for such an analysis is a massive scale data set known as a GIS, or geographic information system. This data set, typically contained within a software package, contains information regarding many aspects of terrain and geography, and specifically for this case, wind speeds. Data is typically composited from long term meteorological studies of wind speeds from each data sampling area. Although these data are far from being complete for the entire US, there is sufficient data to interpolate and develop measurements for most of the inhabited areas of the US. Currently, the best models contain data points at a spatial resolution up to 1km, which is very detailed considering the total area of the US is 9,161,923 km^2 (72).

Data is typically collected from an elevation of 50m above the ground, proving data directly suitable to wind turbines with a hub height of the same elevation. However, newer estimates are now available for some areas using data take at the 80m level, reflecting the increasing hub heights of modern turbines. This of course results in a greater overall resource assessment compared to the 50m data, as wind speed increases with height. Even if 80m data is not available, it is possible to obtain accurate estimations by using well known relations between elevation and wind speed, known as shear laws, which are based on simple power expressions.

Once suitable data is obtained for the desired area of study, the GIS data must then be combined with similarly extensive data on land use in the region, as only a fraction of total land is actually suitable for wind farm development. To understand what types of restrictions are used for land availability, the system used by the NREL to develop their wind resource estimates is presented below. By using such a system, it can be assured that the resource estimates developed are actually realistic and reflect only what wind capacity could actually be harvested by wind farms.

<u>Table 12: Standard NREL land restrictions (73)</u>



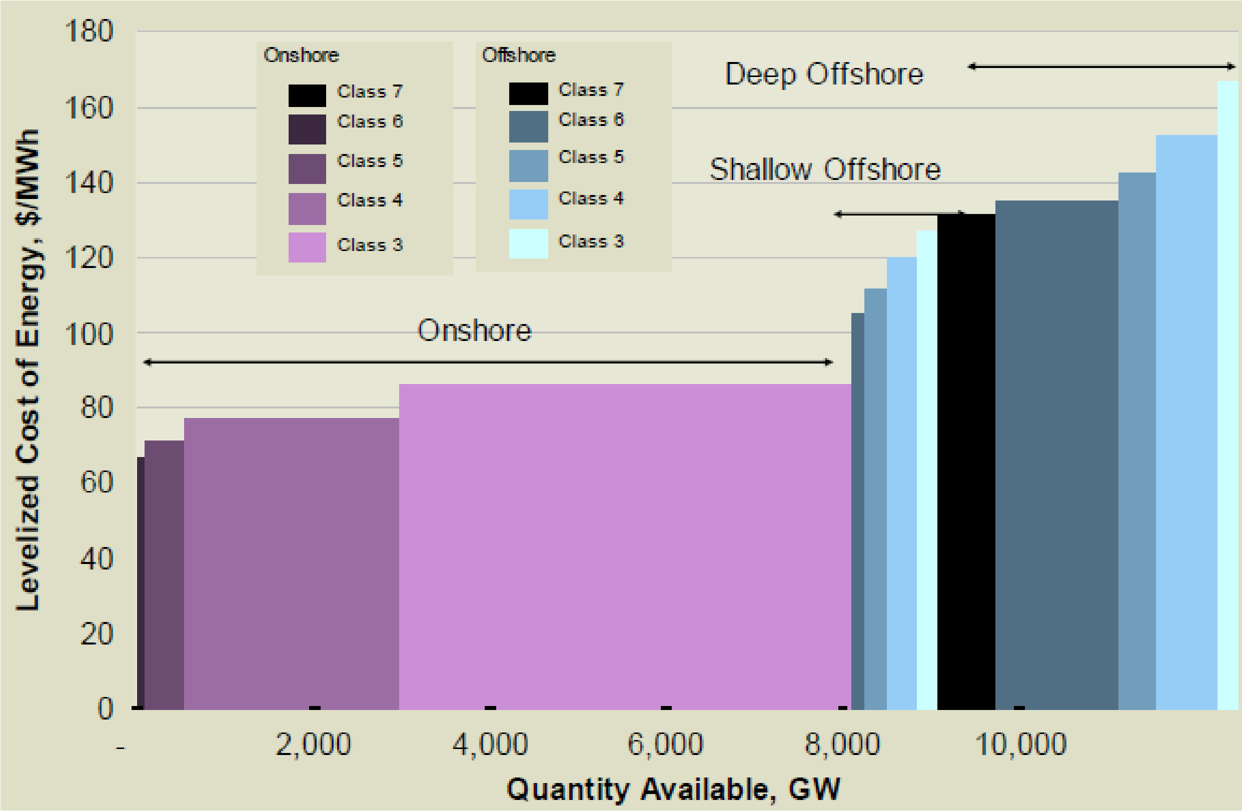
Criteria	Rationale
Any National Park Service and Fish and Wildlife Service Managed lands	These lands are environmentally sensitive
Any federal lands designated as park, wilderness, wilderness study area, national monument, national battlefield, recreation area, national conservation area, wildlife refuge, wildlife area, wild and scenic river or inventoried roadless area.	These lands are assumed to be environmentally or culturally sensitive lands
State and private lands equivalent to the above category, if data is available	These lands are assumed to be environmentally or culturally sensitive lands
Airfields, urban areas, wetlands and water areas	These areas are unsuitable for wind development
Buffer zone of 3 km surrounding the previous categories	
Areas with slope greater than 20%	Areas of high slope are difficult to construct wind farms and may be environmentally sensitive
Areas that do not meet a density of 5 km^2 of class 3 or better resource within the surrounding 100 km^2 area.	Small amounts of land with low wind potential are not generally economic to develop
50% exclusion of remaining Forest Service lands (including national grasslands)	Forest service land may be environmentally sensitive and it is unrealistic to assume all FS land would be open to wind development
50% exclusion of remaining Department of Defense lands	DoD land may not be open to wind development.
50% exclusion of state forest land, where GIS data is available	As with FS land, state forest may not be open to wind development
50% exclusion of non-ridgecrest forest. If an area is non-ridgecrest forest on Forest Service land, it is just excluded at the 50% level once.	Forest land is environmentally sensitive and may not be suitable for development.

Source: NREL.
Note: 50% exclusions are not cumulative

The next step in such an analysis is to estimate the density with which wind turbines can be placed. In individual wind projects, this is determined by a variety of factors and local conditions, but typical average values can accurately be used. In the particular analysis studied, this density was give as 5 MW/km^2, which tends to reflect the overall average for large wind farms (73). One important note with regard to this density is the actual land usage of the turbines. While this figure represents the overall amount of land which a wind farm occupies, the turbines themselves have relatively small footprints, and therefore a vast majority of the wind farm "occupied land" is in fact open space. This has proved quite beneficial in areas of the Midwest, where farmers rent out their land to turbine owners, who only need a small fraction of their useable farmland for turbine construction.

The results of one of the most recent studies of US wind resource potential performed by a joint effort of the DOE and Black and Veatch is presented below. It is given in the form of a supply curve, which shows the estimated cost of producing power from each wind class.

Figure 66: US wind supply curve, 2010 Busbar cost (73)



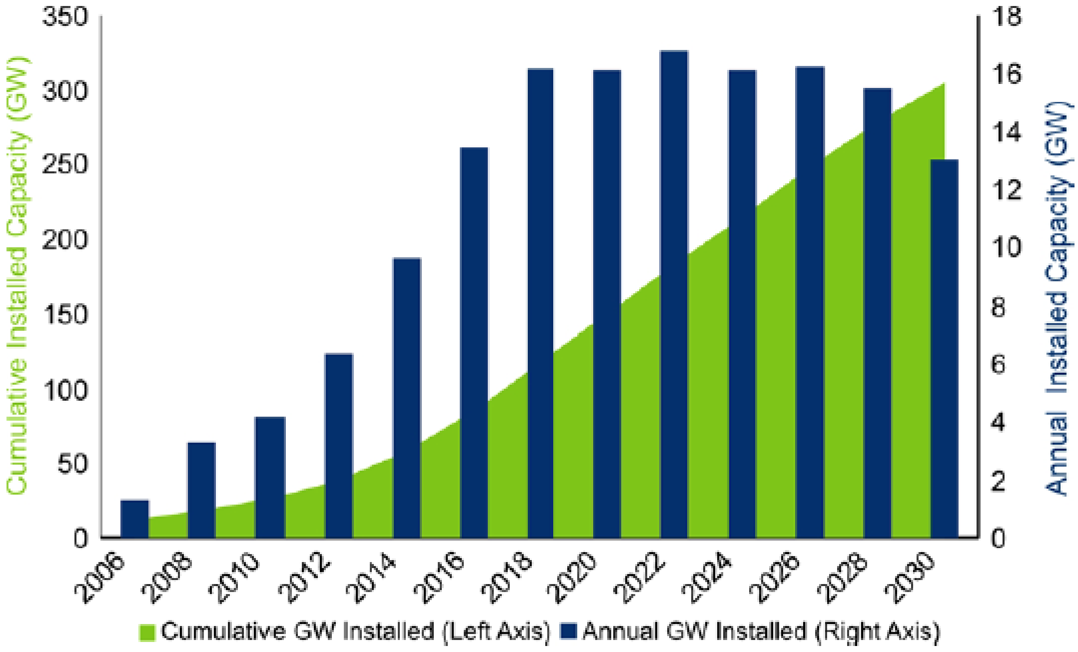
As can be seen, the onshore potential alone is enormous. For comparison, the 2009 total US generating capacity was approximately 1,100 GW at the end of 2008 (1). There is clearly an extremely abundant supply of wind capacity in the US, enough to meet over 10 times the present total generating capacity, and supply US energy needs well into the future. With the current installed wind capacity of just over 35 GW, the US is just beginning to tap this tremendous resource with less than 0.5% utilization.

Another interesting conclusion can be drawn from these figures. When considering the average turbine density of 5 MW/km^2, the total approximate land area required to meet all current US electric needs from wind can be calculated. From the density, it would require 200km^2/GW capacity, so 1,100 GW would require 220,000 km^2, or approximately 2.4% of total US land area. This is approximately the area of the state of Idaho. This may seem like an unreasonably large amount of land use, but again recall that the actual foot print of the turbines and their infrastructure is much smaller than the overall land area which they are spread across, leaving plenty of open space.

4.4 Analysis of the 20% Wind by 2030 Scenario

A significant amount of the resources utilized in the research of this project were provided by a groundbreaking report jointly completed by the DOE, NREL, Black & Veatch engineering consultants, and the AWEA in 2007. The basis for this report was the modeling and prediction of the feasibility of wind energy reaching a 20% electric generation market penetration by the year 2030. The intention was not to predict if wind energy would grow to this amount, but merely identify whether such a scenario was actually plausible given the current state of the wind industry.

Figure 67: Annual and Cumulative Wind Installations by 2030 (73)



The goal of 20% by 2030 is rather lofty based on the current percentage of electricity that wind provides, nevertheless, this study shows that achieving this number is feasible. In the US, there are more than enough wind resources to power the entire country, however, substantial research and planning is needed to determine the optimal sites for wind turbines. Questions that arise when talking about integrating this many turbines involve things like the amount of materials and resources for manufacturing. There does seem to be sufficient materials and man power needed to design and install such a large amount of projects in a relatively short time.

Turbines must continually be improved in order to meet this goal, whether the improvements are mechanical and design improvements, or whether they are additional benefits provided to wind generation companies, investors and consumers. Assuming that the turbines will continue to gain in efficiency, and that there are sufficient sites and resources to build turbines, this scenario seems quite reasonable. One of the most important issues affecting the future of wind growth is the ability to easily integrate new capacity into the existing electric transmission system. Once this is achieved, it is very much possible for the US to obtain 20% or more of its electricity from wind turbines by 2030.

If this goal is ever reached, the benefits will be vast. Benefits of this scenario can be seem in the environment, with reductions in carbon dioxide emission reaching as much as 825 metric tons annually, and reductions in cumulative water use by 4 trillion gallons. Other benefits will be seen in federal and local governments, energy prices, and to the American citizens by providing jobs in the wind industry.

4.5 Benefits of Increased Wind Energy Production:

There are many benefits to the further development of wind energy in the US from both a health and economic standpoint. The largest health impact that wind energy can potentially provide is the avoidance of thousands of pounds of carbon dioxide each year from fossil fuel energy generation. The following table lists the emission factors for various fossil fuel energy generation sources.

Table 13: Carbon Dioxide Uncontrolled Emission Factors (74)

Fuel	Pounds of CO_2 per million Btu	Pounds of CO_2 per MWh 3.413
Bituminous Coal	205.30	700.69
Distillate Fuel Oil	161.39	550.82
Geothermal	16.600	56.656
Jet Fuel	156.26	533.32
Kerosene	159.54	544.51
Lignite Coal	215.40	735.16
Municipal Solid Waste	91.900	313.65
Natural Gas	117.08	399.59
Petroleum Coke	225.13	768.37
Propane Gas	139.18	475.02
Residual Fuel Oil	173.91	593.55
Synthetic Coal	205.30	700.69
Subbituminous Coal	212.70	725.95
Tire-Derived Fuel	189.54	646.90
Waste Coal	205.30	700.69
Waste Oil	210.00	716.73

1 kWh = 3413 Btu

1 MWh = 1000 kWh

1 MWh = 3.413 Million Btu

Wind energy is beneficial to the environment in more ways than reducing greenhouse gases. Increased generation from wind energy allows for less use of natural resources like fossil fuels and water. Wind energy uses much less water than traditional energy sources as shown in the following chart.

Table 14: Water Consumption of Energy Generation Sources (75)

Technology	Gallons/kWh	Liter/kWh
Nuclear	0.62	2.30
Coal	0.49	1.90
Oil	0.43	1.60
Combined Cycle Gas	0.25	0.95
Wind	0.001	0.004
Solar	0.030	0.110

Wind energy will not completely phase out fossil fuels anytime soon. However, by reducing some of our dependence and diversifying our energy sources, wind energy can help to stabilize energy prices in the US. Since renewables use no fuel they are less susceptible to price increases from inflation. In addition, renewable energy sources such as wind are widely available across the US and never need to be imported like some other energy fuels. Wind energy can help rural economies as well, in small scale terms. Farmer and landowners can now install wind turbines on their land and make a profit selling the energy to power companies.

Results and Conclusions

It has been clearly established by this report that the current sources of energy used in the US cannot be relied upon indefinitely. The issues of energy independence and CO_2 emission reduction have certainly become important national concerns recently, although their still remains non-trivial uncertainty regarding the true role of CO_2. Although there arguably exists a majority who support the pursuit of renewable energy on these grounds, there are still many powerful interests who would like to promote continued use of fossil fuel based energy sources. However, regardless of whether or not the need for renewable energy sources can be argued on these two issues alone, the indisputable fact that fossil fuels are a finite resource, which is being consumed much faster than it is produced, cannot be circumvented. For this reason, the need for greater renewable energy sources in the near future can be firmly established.

In section 2 of this report, the details of fossil fuel reliance in the US were clearly examined, and it was shown that the dependence is very significant and extends to all consumption sectors. More importantly, the likely future demand for energy in the US was also examined and predicted based on linear modeling. These results both show that a growth in energy demand of over 35% is very likely over the next 20 years alone. This section went on to also analyze the remaining fossil fuel resources which are likely to be obtainable. Although significant debate still exists on this topic, the simple modeling performed showed that traditional oil resources would be fully depleted by 2060. If this is plausible, however, then the situation is even more dire, as oil prices would increase tremendously well before the entire resource is actually consumed. Both of these findings together show that there in fact does exist a real need for renewable energy sources right now, and even more so in the near future.

With the clear need shown for greater development of renewable energy sources, section 3 examined the prospective of wind energy specifically. From background research and some of the findings in section 2, the authors determined that wind energy is presently the most likely renewable energy candidate to be able to supply significant amounts of power on the national scale. With this determination, a technical and feasibility analysis of wind energy technology was carried out. One of the key findings was that wind technology as a whole has undergone significant growth and development over the past ten years, and is presently a fairly mature, commercialized technology. With the assistance of federal and state financial incentives for renewable energy sources, and the steady decline of its manufacturing costs, wind energy has been able to compete economically with traditional fossil fuel generation sources. Although significant future improvements are likely and would be beneficial to the industry, wind technology as it stands is a more practical and established solution than its nearest renewable competitors such as photovoltaic solar power. This is clearly and undeniably demonstrated in the analysis of the recent history of new US generating capacity. From 2002 to 2008, wind energy went from making up only about 2% of new electric capacity installed that year, to over 42% of the total new capacity in 2008. Over this same period, the growth of all other renewable sources combined went from making up less than 1% of new capacity to only about 4% of new capacity in 2008. Wind has clearly established a strong lead in not only the renewable energy field, but also among traditional electric generation sources. In 2008, wind energy was only surpassed by new natural gas installations, which made up about 48% of the new capacity that year. The results of this analysis would indicate that there are no major remaining technical hurdles with regard to wind technology itself, and that it certainly has the capability to continue its growth on the national scale.

Finally, this report sought to determine if wind energy could potentially supply a large portion of US energy needs in the near future. A vision was laid out outlining a future in which fossil fuel use has been significantly reduced by the use of wind energy. This description provides a glimpse into one possible situation in which both electric and transportation energy sources are ultimately supplied by the wind. In order to give some validation to such a scenario, the potential US wind resource was examined and shown to have the physical capacity to provide many times the current total US energy need. The question then remained as to how much of the total US generating capacity could actually come from wind alone, while maintaining reliability. The scenario analyzed was that of 20% electric generation from wind energy by the year 2030. Such a development would require a near 10 fold growth in installed US wind capacity over the next 20 years. This represents a large feat, but one which has at least been demonstrated in terms of the necessary growth rates by wind energy in the past. The major limiting factors to the realization of this scenario were determined to be not wind technology itself, or the lack of suitable wind resources, but rather the capability of the current US electric grid system. Two particular significant issues were identified. The misalignment of wind energy resources and electricity demand centers is difficult to overcome, as the current grid lacks the long distance capacity needed to carry energy to where it is needed most, often far from the remote areas where winds are strongest. Second, the grid system lacks the level of interconnectedness required for large percentages of wind energy penetration. With the current system, local scale back up generation would be necessary as wind penetration increases within the particular grid region, due to winds' inherent variability. However, it is demonstrated that a grid system with wider scale interconnection would be able to overcome this issue, and more evenly distribute electric capacity and demand across broader areas. Although these are currently standing issues which will hinder future wind energy growth, the ability to overcome them already exists. It will then be in the hands of the nations’ infrastructure planners to make the necessary investment of time and money to develop a long term solution for the grid system. Finally, it was shown that the benefits of such a system will actually outweigh the initial costs in the long-term.

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