The Future of Electricity

Electricity Today, Drivers of Change, and Electricity Tomorrow

SCHOOL OF PUBLIC AND ENVIRONMENTAL AFFAIRS

INDIANA UNIVERSITY

A V600 Capstone Course

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EXECUTIVE SUMMARY

This report examines the state of electricity today and forecasts global electricity generation and consumption over the next fifty years using the changes that are predicted to occur. While demand for electricity today is predominantly located in developed countries, it is also increasing in developing countries. Electricity currently is generated from a mix of non-renewable and renewable supply sources and is distributed through increasingly taxed transmission systems. Drivers of change affecting electricity's future include population and economic growth, climate change, energy conservation and resource availability.

Key findings of this report include that global consumption and generation of electricity will increase 350 percent over the next 50 years. The relative mix of fuel sources will remain largely unchanged, though generation technologies will become less carbon-intensive due to concerns like climate change. However, for climate change mitigation to be effective, it will require the abatement of emissions, particularly in the developing world. Country-specific case studies of China, Brazil, France, and the United States follow the main body of the report to provide specific illustrations of country-specific situations and geopolitical considerations.

COURSE INFORMATION

A V600 Capstone course represents a culminating experience for students in the School of Public and Environmental Affairs (SPEA) who receive the Master of Public Affairs (MPA) degree, the Master of Science in Environmental Science (MSES) degree, as well as joint Master's degree programs such as the MPA/MSES, MPA/JD, and MSES/JD. Capstone coursework provides students with an opportunity to apply knowledge gained from their unique concentration areas at SPEA. The work done by capstone students integrates science, economic, political, and social considerations studied in the classroom and applies these factors to a current policy issue. Capstone courses are designed to challenge students to extend beyond their personal areas of study and learn about a complex subject area they may little prior knowledge of.

Course Background

A recent article in *Nature* observed that, "Electricity generation provides 18,000 terawatt-hours of energy a year, around 40% of humanity's total energy use. In doing so, it produces more than 10 gigatonnes of carbon dioxide every year, the largest sectoral contribution of humanity's fossil-fuel derived emissions."[1] Over the next 50 years, the demand for electricity will almost certainly grow, in no small part because of the expected economic growth in countries such as China and India. At the same time, it seems likely that concerns about carbon dioxide and other greenhouse gas emissions and global warming will also grow. It does not seem like too much of an exaggeration to say that the world's attitude toward electricity seems to be on a collision course. The focus of this capstone is to forecast how these competing forces will sort themselves out and what policies might be considered.

In response, this particular capstone sought analyze the future of worldwide electricity in the next 50 years. Students examined the future of electricity on a global scale as well as on a regional level. Globally, students were asked to look at electricity demand and changing technologies that will impact that demand. Regionally, students examined Brazil, China, France, and the United States.

An important task is to assess emerging technologies that claim to be improvements over current approaches. This analysis considers where each emerging technology is in its development cycle and what hurdles remain to widespread use. Although technological challenges can impede implementation, other challenges including economic, environmental, social, political, and cultural factors also impose significant barriers.

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[1] "Electricity Without Carbon," *Nature*, Volume 454, 14 August 2008.

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Sponsor:

The Indiana University Center for Research in Energy and the Environment (CREE), which is administered by the School of Public and Environmental Affairs and is a member of the Indiana Consortium for Research in Energy Systems and Policy.

CREE assembles top scholars from multiple disciplines to conduct innovative, timely and relevant research in the broad area of energy, focusing specifically on:
- advanced fossil fuels and nuclear power;
- alternative or renewable energy resources;
- local and regional carbon cycle dynamics;
- environmental and economic consequences of energy production and distribution.

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AC- Alternating Current
ACL- Ambiente de Contratação Livre (Brazil)
AMD-Acid Mine Drainage
ANDRA- National Radioactive Waste Management Agency (France)
ANEEL-National Agency of Electricity (Brazil)
BES-Bulk Energy and Storage
BIPV-Building Integrated Photovoltaic
BkWh-Billion Kilowatt Hour
Btu-British Thermal Units
CCS-Carbon Capture and Storage
CCX-Chicago Climate Exchange
CEMIG-Companhia Energética de Minas Gerais (Brazil)
CER-Certified Emission Reduction
CGE-Crisis Management Board (Brazil)
CO_2-Carbon Dioxide
COPEL-Companhia Paranaense de Energia (Brazil)
CSP-Concentrated Solar Power
DOE-Department of Energy
DSM-Demand Side Management
€-Euro
ECX-European Climate Exchange
EDF- Electricité de France (France)
EIA- Energy Information Administration
EM-Energy Management
EPACT-Energy Policy ACT
EPE-Empresa de Planejamento Energético (Brazil)
EUA-European Union Allowance
EUETS-European Union Emissions Trading Scheme
GDP-Gross Domestic Product
GHG-Green House Gas
GW-Gigawatts
Hg- Mercury
Hg-p-Particle Bound Mercury
Hg^0-Vapor- Phase Elemental Mercury
Hg^{2+}-Vapor-Phase Oxidized Mercury
HVAC- Heating, Ventilating and Air-Conditioning
HVDC-High Voltage Direct Current
IDM- Industrial Demand Module
IEA-International Energy Agency
IGCC-Integrated Gasification Combined Cycle

IPCC-Intergovernmental Panel on Climate Change
ITC-Investment Tax Credits
Km-Kilometers
KW-Kilowatts
kW_e-Kilowatt Electricity
kWh- Kilowatt Hours
MAE-Wholesale Electricity Market (Brazil)
MIT-Massachusetts Institute of Technology
MMBtu-Million British Thermal Units
MW-Megawatts
NAICS- North American Industry Classification System
NDRC- National Development and Reform Commission (China)
NEMS- National Energy Modeling System
NETL-National Energy Technology Laboratory
NGCC-Natural Gas with Combined-Cycle
NO_x-Nitrogen Oxides
OECD- Organization for Economic Co-operation and Development
ONS-National Electricity System Operator (Brazil)
PC-Pulverized Coal
PM-Particulate Matter
PPP-Purchasing Power Parity
PQB-Power Quality and Bridging
PTC-Production Tax Credits
PV-Photovoltaic
RESEB-Project for the Restructuring of the Brazilian Electric Sector (Brazil)
RGGI-Regional Greenhouse Gas Initiative
RMB-Renminbi (China)
UNEP-United Nations Environment Programme
SERC-State Electricity Regulatory Commission (China)
SO_x-Sulfur Oxides
SO_2- Sulfur Dioxide
Tg-Teragrams
TWh- Terawatt hours (China)
WEC-Wave Energy Conversion
WEC-World Energy Council
WEO-World Energy Outlook

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ABSTRACT

World population growth and increasing global reliance on electricity will dramatically expand the total quantity of electricity produced and consumed in the next fifty years. While the relative mix of fuel sources will remain largely unchanged, technologies used to generate electricity will become less carbon intensive. This project discusses the current state of electricity at the global level, and forecasts electricity generation, consumption, and delivery to 2060. Country case-studies of China, Brazil, France, and the United States provide specific illustrations of country-specific situations and geopolitical considerations.

 The primary factors that will drive change in the future of electricity are population growth, economic growth, concerns about climate change, and resource availability. By the year 2060, a global population near 10 billion will have higher median incomes and consume 350% more electricity than current levels. In the near future, increased concerns about global climate change will lead to a price for emissions of carbon dioxide. This will impact the cost of electricity generated from fossil fuels. We project the increased use of nuclear and natural gas to generate electricity in the developed world. However, much of the increased demand for electricity will occur in the developing world, which will be met by a rapid expansion of electricity generation from fossil fuels. Thus, strategies to mitigate climate change will require the spread of less carbon-intensive technologies from developed countries to the developing world. While long-term projections are inherently uncertain, this study provides some insight into how multiple competing forces will shape the future of electricity.

Chapter I: Electricity Today

World electricity demand has more than doubled over the last 15 years due to growth in world population and increasing per capita incomes. Total world electricity consumption was approximately 7.332 trillion kilowatt hours (kWh) in 1980, and by 2006, the global community was consuming around 16.378 trillion kWh of electricity (Energy Information Administration, 2008).

As shown in Figure 1 below, breakdown of world electricity generation shows clear differences between countries that are and are not members of the Organization for Economic Co-operation and Development (OECD). Coal is dominant for both, though non-OECD members are more reliant on coal as an electricity fuel source. Coal comprises 45 percent of the non-OECD fuel mix, compared to 37 percent for OECD members. Hydroelectric generation is more prevalent in non-OECD countries, at 21 percent of the non-OECD fuel mix versus 13 percent of the OECD mix. Natural gas is the same for both groups, at 20 percent. Comparing generation, non-OECD countries produced 8.5 trillion kWh of electricity in 2006, while OECD countries produced 10.5 trillion kWh the same year.
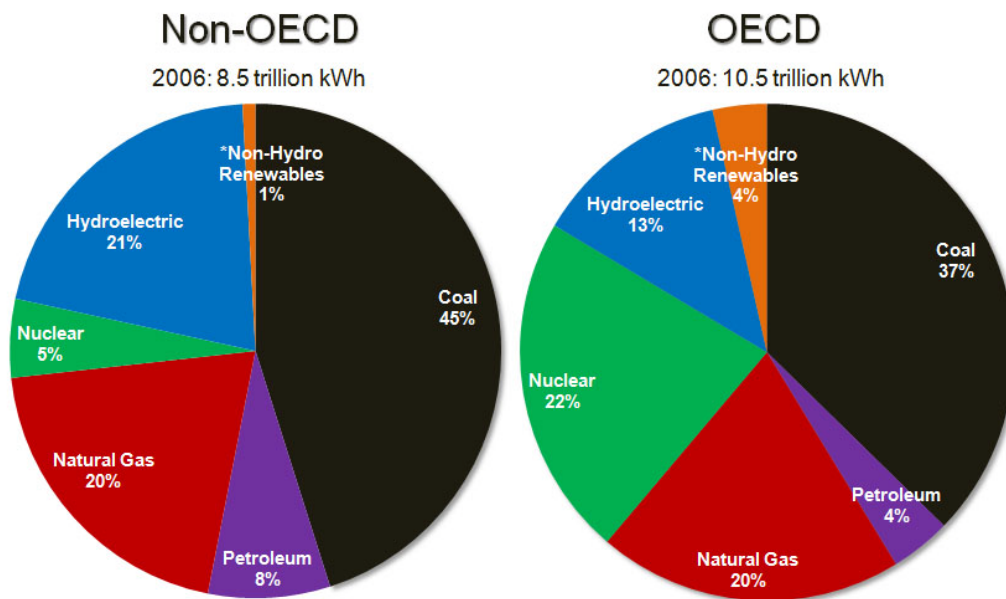
Figure 1: Electricity Generation Mix[2]

DEMAND BY SECTOR TODAY

Three main sectors of electricity consumption drive demand for electricity throughout the world: industrial, commercial, and residential.

Industrial Sector

The Energy Information Administration (EIA) defines the industrial sector as an energy-intensive sector that includes all facilities and equipment for manufacturing, processing, or assembling goods. The industrial sector as defined by the North American Industry Classification System (NAICS) includes the

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[2] Sources: IEA 2006 *World Energy Outlook* and EIA 2006 *International Energy Outlook.*

following types of activity: manufacturing; agriculture, forestry, fishing, and hunting; mining, including oil and gas extraction; and construction. Overall, electricity use in this sector is largely for process heat, cooling and powering machinery, with lesser amounts used for facility heating, air conditioning, and lighting (Energy Information Administration, 2009).

Every year the EIA submits an Annual Energy Outlook, which is based on the National Energy Modeling System (NEMS),[3] the US Department of Energy's energy policy model. Even though the EIA primarily projects US demand by major sectors, the NEMS provides a reference point to compare industrial demand globally. The EIA also uses the 2008 Industrial Demand Module (IDM) which divides "industry" into 21 manufacturing industries (energy-intensive and non energy-intensive) and six non-manufacturing industries (Energy Information Administration, 2008).

Industrial sector demand for electricity has grown over the past 25 years with the expansion of industrial activity in both developing and developed countries. Increased industrial sector demand for electricity is the result of rapid development and urbanization in developing countries. The major demand determinants in the industrial sector are generation and supply; price is a secondary consideration.

Demand for industrial electricity is generally inelastic (Polemis, 2007). Studies show the price elasticity of industrial electricity demand to range from an average of -0.71225 in the long-term to -0.3165 in the short-term (Lijesen, 2007).

The fixed retail price of electricity for the industrial sector is established under an agreement between the utility companies and the government agency or regulators that oversee the utility market. These fixed rates can differ between countries and even within a country, such as in the US. Yet fixed rates can distort markets since the use of fixed prices makes consumption insensitive to the cost of electricity production (Office of Air and Radiation, 2001).

Commercial Sector

The commercial sector, which is also referred to as the service or tertiary sector, consists of a number of "principal suites." These suites include banking and finance, corporate headquarters, producer services such as consulting, gateways like airports and seaports, government capitals, tourism, advanced technology services, creative and design services, education and research (Hutton, 2004).

The commercial sector consumes less electricity compared to other demand sectors (Energy Information Administration, 2002). Although some commercial sector organizations utilize electricity for purposes such as water supply or streetlights, the commercial sector consumes a majority of its electricity through building use (Energy Information Administration, 2002). Heating, ventilation, and air-conditioning (HVAC) systems account for most of the electricity used in the commercial sector(U.S. Congress, Office of Technology Assessment, 1993, p. 80). In the commercial sector, the primary driver of electricity demand is floor space. Other characteristics of commercial buildings that determine commercial sector electricity use include the age and location of buildings and the commercial activities of the organizations(Energy Information Administration, 2002).

Additionally, the commercial sector represents an area of increasing demand for electricity worldwide. In its Annual Energy Outlook 2008, the EIA predicted a 29 percent increase in total US electricity sales.

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[3] The National Energy Modeling System focuses primarily on US energy markets. The NEMS projects energy production, consumption and prices based on a model that controls for assumptions about macroeconomic and financial factors, effects from the world markets, supply projections, behavioral/technological projections as well as population demographics. The NEMS further disaggregates demand projections by major sector – residential, commercial, industrial, and transportation with flexibility by US region. In addition to dissecting demand by major sector, the NEMS also models the electricity and energy supply markets, along with distribution and natural gas transmission. The US Department of Energy uses NEMS as the basis for most of their energy policy analysis (Energy Information Administration, 2000).

Within that increase, 49 percent is due to increased demand for products, floor space, and services (Energy Information Administration, 2008).[4]

Floor space is the primary driver of electricity demand in the commercial sector. Demand in the commercial sector is inelastic in both the short-term and long-term. Studies show the price elasticity of commercial electricity demand to range from an average of -0.27 in the short term to -0.975 in the long term (Lijesen, 2007).

Residential Sector

The EIA defines the residential sector as consisting of private living quarters, and most commonly using energy for space and water heating, air conditioning, lighting, refrigeration, cooking, and operating various other appliances (EIA, Energy Glossary - R, 2009). However, the residential sector differs in developing and developed countries. Residential electricity demand varies widely between OECD and non-OECD nations. Economic growth in developing countries will result in higher average household incomes. As a result, common household conveniences found in developing countries such as heating, air conditioning, lighting, and other electrical appliances will become more accessible. Saturation of end use residential demand components in non-OECD country households is expected to look increasingly like those in the US and other OECD countries. Figure 2 shows electrical end-use items found in a typical US household.
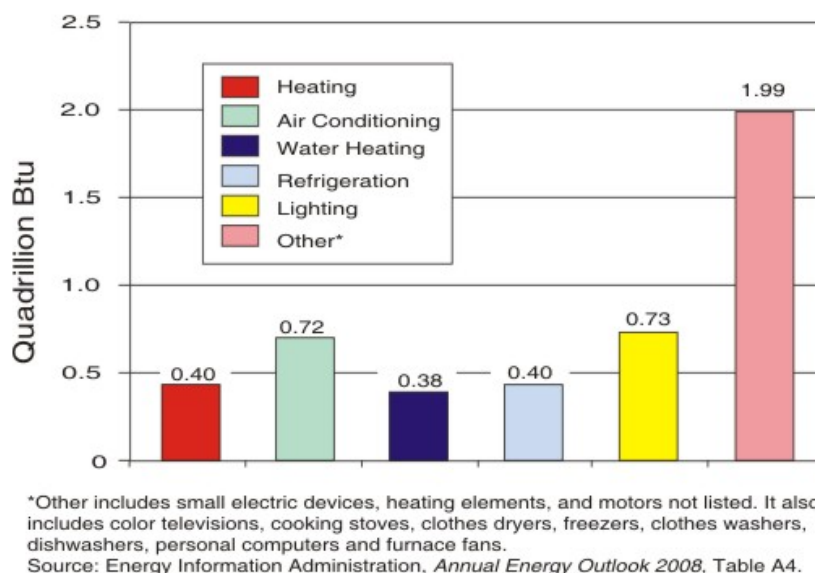

*Other includes small electric devices, heating elements, and motors not listed. It also includes color televisions, cooking stoves, clothes dryers, freezers, clothes washers, dishwashers, personal computers and furnace fans.
Source: Energy Information Administration, *Annual Energy Outlook 2008*, Table A4.

Figure 2: Electrical End Use Items (Energy Information Administration, 2008)

The category titled "other" was the largest demand determinant in a typical US household in 2008. This trend is expected to continue in the future in other OECD countries. Televisions, personal computers, washers and dryers, and dishwashers are part of this category. Electric appliances individually consume a small percentage of total residential demand, but together they represent the largest share of total residential demand. Projected income growth in non-OECD countries will lead to increased electricity consumption from household appliances and small consumer electronics.

Demand in the residential sector is inelastic in both the short-term and long-term. Studies show the price elasticity of commercial electricity demand to range from an average of -0.2238 in the short-term to-0.3958 in the long-term (Lijesen, 2007).

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[4] It should be noted that this is contingent on economic growth, the outlook for which was much different in 2008 than it was today. In this reference case, 39 percent is predicted as the high growth case, which seems much less feasible in light of the current global economic downturn (Energy Information Administration, 2008).

As illustrated, demand for electricity varies across countries and between the industrial, commercial and residential sectors. In considering the future of electricity, it is not only demand that must be considered, but also the generation of that electricity and the supply of materials that will drive that generation.

SUPPLY TODAY

Current generation of electricity comes from various sources. These include coal, natural gas, nuclear power, hydroelectric and other renewable energy sources. This analysis of supply begins with non-renewable energy sources.

COAL GENERATION

Coal is an abundant resource in most countries around the world and is the most commonly used for purposes of electricity generation today. Coal makes up the bulk of current electricity generation and with major stockpiles in the US and China, it will continue to be dominant energy source for some time. Pulverized coal-fired power plants (PC) are the most widely used electricity generation technology, accounting for 41 percent of current generation. PC plants generate electricity at the lowest cost per kWh compared to other generation technologies (Appendix A).

The vast supplies of coal not only make it a valued source for electricity generation, but it remains relatively cheap when compared to its fossil fuel competitors. Coal prices range from about $1 to $2 per million British thermal units (Btu), whereas natural gas and oil range from about $6 to 12 per million Btu (Massachusetts Institute of Technology, 2007).

Capital costs for coal fueled power plants of $1500 to $1900 per kilowatt electricity (kW$_e$), with the variation reflecting differences between PC and more complicated systems such as Integrated Gasification Combined Cycle (IGCC) power plants. This is based on 2007 from Department of Energy (DOE) National Energy Technology Laboratory (NETL) baseline estimates for fossil energy plants. Electricity prices for coal generation range from US$0.03 to 0.05/kWh, before the inclusion of transmission and distribution costs. Utility bill costs are still a few cents higher. Capital costs do not include carbon emissions ranging from 0.78 - 0.83 kg/kWh for PC or IGCC, or the negative externalities of coal extraction. The price of Carbon Capture and Sequestration (CCS) is not included, as it is currently not a wide-spread abatement technology. A full explanation of these prices is available in appendices A and C.
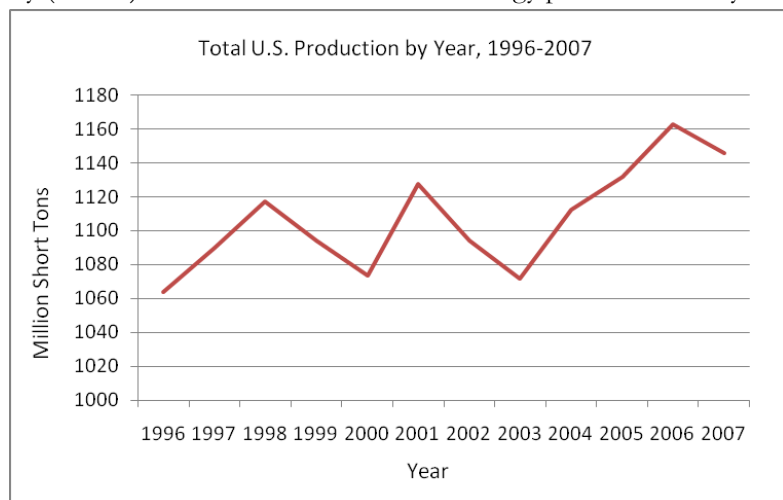

Figure 3: Total Annual US Coal Production
(World Coal Institute, 2008)

Coal is the default material used to produce electricity for a number of reasons: the stability of the global coal supply, the fact that coal production is not subject to severe production disruptions, and the security of transportation and trading of coal (Massachusetts Institute of Technology, 2007). In 2007, two of the three largest coal reserves belonged to the US and China. The US has the largest proven coal reserves, which total over 242,721 million tons. China's coal reserves total 114,500 million tons (British Petroleum Inc., 2007). With these reserves at their disposal, both the US and China will use coal as their main fuel source to generate

electricity in the next fifty years. In 2007, US production of coal was 1,145.6 million short tons, mostly attributable to weather-related increased demand (Figure 3). This trend is typical, as coal production has been increasing overall since 1996 (Energy Information Administration, 2008c).

According to the World Coal Institute (2008), coal produces 26 percent of the world's primary energy supply, and 41 percent of the world's electricity.[5] As Table 1 illustrates, many regions rely on coal to meet a large proportion of their current electricity needs, and this trend is expected to continue into the future under an analysis by the EIA.

Limitations of Coal

Despite its abundance and stable prices, there are many well-known environmental consequences from the use of coal in the production of electricity. PC plants, the cheapest and most widely used generation technology, emit large amounts of pollutants and greenhouse gasses (GHG) per kWh relative to other generation technologies. The emissions that result from the combustion of coal to produce electricity are a concern because they contain carbon dioxide (CO_2), nitrogen and sulfur oxides, and particulate matter (Smil, 2003, pp. 106-107).

Table 1. Percentage of Net Electricity Generated by Coal in 2005 and Predicted to Occur in 2030		
COAL	**2005 (percent)**	**2030 (percent)**
USA	49.7	54.2
China	77	84
India	74	65
Japan	30	23
South Korea	41	~36
Australia/New Zealand	Over 70	68
Non-OECD Asia	67.3	72.1
OECD Europe	29.7	22.4
Africa	47	32
Middle East	4.98	3.3
World	41	46
(Energy Information Administration, 2008a)		

CO_2 emissions receive increasing global attention due to being a greenhouse gas, and their impact on global climate change. A study conducted by the Massachusetts Institute of Technology (MIT), predicts CO_2 emissions will rise in the current regulatory climate. CO_2 emissions from non-OECD countries are predicted to increase by 33.7 percent, while emissions from OECD countries and the US alone are predicted to rise 9.3 percent and 10.2 percent respectively (Massachusetts Institute of Technology, 2007). This increase in emissions, especially in light of concerns regarding global climate change, demonstrates the need for global CO_2 emissions regulation.

The release of mercury (Hg) is another issue associated with the use of coal in electricity generation. The mercury present in coal is emitted during the combustion process as one of three types: "(i) particle-bound mercury (Hg-p); (ii) vapor-phase elemental mercury (Hg^0), and (iii) vapor-phase oxidized mercury (Hg^{2+})"(Mukherjee, Zevenhoven, Bhattacharya, Sajwan, & Kikuchi, 2008). Mercury is a pollutant of concern due to the ease with which it can move large distances and its toxicity to both humans and the surrounding environment (UNEP Chemicals Branch, 2008). One study estimated that in 1990 coal combustion activities emitted 1.46 kilotons of mercury into the atmosphere (Mukherjee, Zevenhoven, Bhattacharya, Sajwan, & Kikuchi, 2008), while the United Nations Environment Programme (UNEP) estimated that 482.5 metric tons of mercury were released into the atmosphere from mostly coal-fueled power plants (UNEP Chemicals Branch, 2008). Estimates indicate that power-generating facilities in the US release approximately 46 tons of mercury into the atmosphere on an annual basis(Electric Power Research Institute, 2009).

Sulfur oxides (SO_x) and nitrogen oxides (No_x) are additional emissions from electricity generation activities. Sulfur oxides, predominantly in the form of sulfur dioxide (SO_2), are a type of emissions that

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[5] These figures vary because primary energy statistics are recording mobile and non-mobile sources, while electricity solely records non-mobile (World Coal Institute, 2008).

are known contributors to a number of health and environmental concerns. Both SO_2 and NO_x negatively impact human health by impairing or damaging the respiratory system (Peng, Wu, Liu, Johnson, Shah, & Guttikunda, 2002; Burtraw, Evans, Krupnick, Palmer, & Toth, 2005). NO_x contribute to such problems as ground-level ozone formation, respiratory problems, and adverse effects to ecosystems due to increased nutrient inputs (U.S. Environmental Protection Agency, 2008).

SO_2 and NO_x emitted from power plants create acid rain as a result of their combining with other atmospheric elements to form sulfuric and nitric acid(U.S. Environmental Protection Agency, 2007b). Acid rain can then be deposited into aquatic and terrestrial habitats over large distances, resulting in negative impacts on a region's water and soil chemistry (Smil, 2003, p. 109). Acidic storm runoff can release potentially toxic material (e.g. aluminum) from soils where it is available for uptake by plants or released into bodies of water and leach useful minerals and nutrients from the soil, or damage the leaves of plants, all of which can affect plant growth (US Environmental Protection Agency, 2007a; US Environmental Protection Agency, 2007b).

In 2007, the US emitted 9,042 thousand metric tons of SO_2 from conventional coal and cogeneration plants (Energy Information Administration, 2009). Asia emitted 38.5 teragrams (Tg) of SO_2 in 1995. By 2000, emissions decreased to 34.4 Tg.SO_2 emissions in China decreased 19 percent between 1995 and 2000, due to decreased economic activity and government actions designed to reduce SO_2 emissions. In 2000, the Chinese government called for a reduction in emission levels from 20.8 Tg to 17.96 Tg by 2005. On the other hand, India's emission levels in 2000 were estimated at 26.4 percent of China's emissions, but coal-fueled power generation is expected to increase and government action to reduce SO_2 is only beginning. Overall, annual SO_2 emissions in Asia are predicted to stabilize at 45 Tg by 2025 (Carmichael, et al., 2002), a level which will result in negative impacts on human health given concentrations of particulate matter.

Particulate matter (PM), which refers to solid and/or liquid airborne particles, are considered a pollutant of concern due to negative health effects, which affect the upper respiratory tract and pulmonary system of humans. Particulates can result from the direct combustion of fuels, such as coal, or from other airborne pollutants (e. g. SO_2).

Besides negative health externalities associated with emissions from power plants, coal mining contributes to environmental externalities as well. Negative environmental externalities are related to abandoned and retired mines. Reclaiming abandoned and retired mines can include a variety of activities designed to restore the land area to the level of quality prior to the establi23shment of the mine. However, because some of the advanced techniques that are employed by ecological engineers were not available to previously abandoned or retired mines, traditional reclamation consists of a reforestation effort. The reforestation effort is not without environmental consequences. Habitat conversion threatens biodiversity, especially when reforestation does not reflect the naturally occurring ecosystem (Dobson, Bradshaw, & Baker, 1997).

Additionally, even after reclamation, mines are a source of acidic drainage that can enter watersheds and effect water quality and pH levels. Even for well-restored mine sites, trace elements present in coal may remain. These elements include arsenic, cadmium, mercury, lead, fluorine, and beryllium. Although the trace levels present in a restored area should pose minimal threat to the ecosystem, the possibility of leachate entering the water table is present and synergistic effects of these metals and other system elements have not been well-documented (Committee on Health and Environmental Effects of Increased Coal Utilization, 1980). Because of the interaction between acid mine drainage (AMD) and heavy metals, the remaining environment may not be a suitable environment for naturally occurring organisms (Ledin & Pedersen, 1996).

NATURAL GAS GENERATION

Natural gas power plants represent the second most common and fastest growing electricity generation technology with an electricity price of approximately US$0.04 to 0.08 cents/kWh. The growth of natural gas power plants stems from their low capital costs of about US$450 to 550/kW$_e$ and relatively quick construction time compared to other generation technologies(Appendix A). Carbon emission costs are 0.36 kg/kWh. Operation costs for natural gas plants remain higher than those for coal or nuclear plants (Energy Information Administration, 2009).

High thermal efficiency capabilities also contribute to the importance of natural gas power plants in electricity production. The most basic natural gas-fired electric generation consists of a steam-generated unit that burns fossil fuels in a boiler. Typically, only 33 to 35 percent of the thermal energy is used to generate the steam that is converted into electrical energy. Other widely used technologies are gas turbines and combustion engines; however, these have lower efficiency in energy conversion. Many of the new natural gas-fired power plants are equipped with combined-cycle units. These units contain both a gas turbine and a steam unit. Natural gas power plants with combined-cycle (NGCC) units can achieve up to 50 percent efficiency. Other fossil fuel generation technology, such as PC and IGCC, can achieve up to 38 and 39 percent efficiency respectively (See appendix A) (US Department of Energy, 2007).

The combustion of natural gas releases small amounts of sulfur dioxide and nitrogen oxides, virtually no ash or particulate matter, and lower levels of carbon dioxide, carbon monoxide, and other reactive hydrocarbons than does the burning of coal or oil (Natural Gas Supply Association, 2009).

A second advantage to natural gas is that its use does not contribute significantly to smog formation. Smog and poor air quality is a pressing environmental problem, particularly for large metropolitan cities. The primary constituent of smog is ground level ozone, which is formed by a series of chemical reactions of carbon monoxide, nitrogen oxides, volatile organic compounds, and heat from sunlight. Smog causes a variety of health issues because it can irritate the respiratory system, reduce lung function, aggravate asthma and inflame and damage the lining of the lung (United States Environmental Protection Agency, 2009). Natural gas contributes less to this problem because it emits low levels of nitrogen oxides, and virtually no particulate matter.

Increasing the use of natural gas power plants from coal and oil power plants would also significantly reduce particulate emissions globally. Particulate emissions also contribute to the degradation of air quality. These particulates can include soot, ash, metals, and other airborne particles. Natural gas emits virtually no particulates into the atmosphere. In fact, emissions of particulates from natural gas combustion are 90 percent lower than from the combustion of oil, and 99 percent lower than coal (Natural Gas Supply Association, 2009).

An additional benefit from the use of natural gas in power generation is that it can significantly reduce acid rain. Acid rain damages crops, forests, wildlife populations, causes respiratory problems and other illnesses in humans. In the US, roughly two-thirds of all SO$_2$ and a quarter of all NO$_x$ come from coal-fired electric generation (United States Environmental Protection Agency, 2009). Unlike coal that contains considerable amounts of sulfur, natural gas emits trace amount of sulfur dioxide and up to 80 percent less nitrogen oxide than the combustion of coal (Natural Gas Supply Association, 2009).

The output of electricity from natural gas can also be flexibly adjusted. Principally, technological advancements in the exploration, extraction, and transportation of natural gas have decreased barriers to entry for emerging suppliers. Consequently, the global output of natural gas has increased. Natural gas reserves are primarily located in Russia, Iran, and Qatar. These nations have 57 percent of proven natural gas supplies (Agency, 2008). Smaller countries have gained entry to the natural gas market. This has decreased their reliance on OECD countries for natural gas supplies. Global proven reserves measure between 6185.694 trillion cubic feet and 6315.770 trillion cubic feet. Proven reserves are those that can be reasonably extracted given the present state of economic and operational conditions (EIA, 2007).

Limitations of Natural Gas

Natural gas power plants are not without their limitations. Although natural gas power plants emit fewer greenhouse gas emissions, methane, in particular, poses negative environmental consequences. Methane is emitted when natural gas is not burned completely or as the result of leaks and losses during its transportation. In addition, the process of extraction and treatment generate additional emissions (University of Strathclyde Physics and Applied Physics Semiconductor Spectroscopy and Devices).

Methane is 21 times more potent than CO_2 over a 100-year period (University of Strathclyde Physics and Applied Physics Semiconductor Spectroscopy and Devices). Although methane emissions account for only 1.1 percent of total US greenhouse gas emissions, they account for 8.5 percent of the greenhouse gas emissions based on global warming potential (Power, 2006). Although methane is more potent, its low concentration makes it contribute much less to greenhouse effects than CO_2.

Natural gas-fired boiler and combined cycle systems also require water for cooling purposes. This amount of water is less than what is required for coal, nuclear, or other fossil fuels. Combustion turbines do not produce any water discharges (University of Strathclyde Physics and Applied Physics Semiconductor Spectroscopy and Devices).

Natural gas prices are also highly volatile, posing security concerns to the supply of natural gas. Figure 4 demonstrates price fluctuations by percentage from 1989 to 2007. This does not include actual costs and only shows how much price can change over time. The International Energy Agency (IEA) has set out two broad categories for gas security risks for natural gas importing countries: long term risk that new supplies cannot be brought on stream to meet growing demand for either economic or political reasons; and risk of disruptions to existing supplies such as political disruptions, accidents or extreme weather conditions.
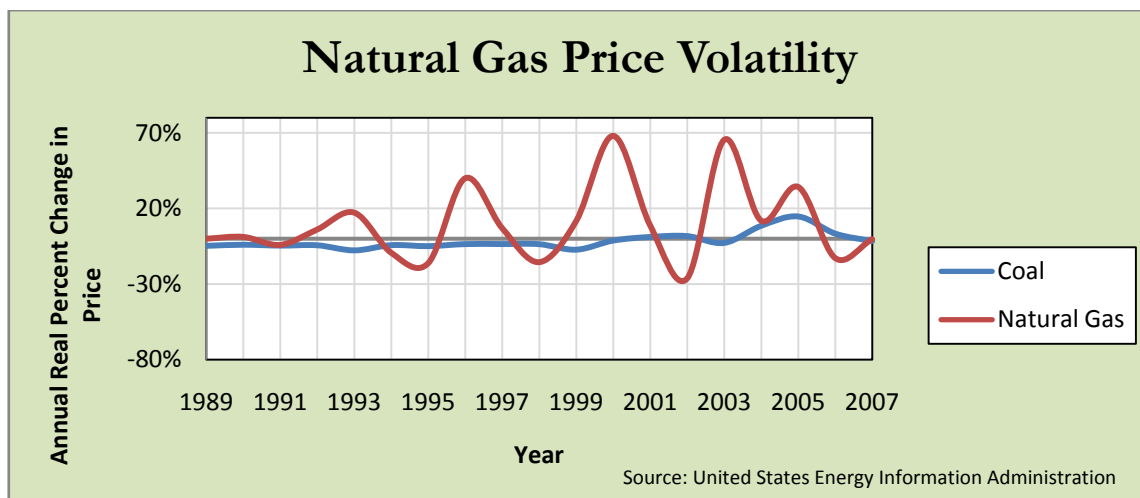

Figure 4: Natural Gas Price Volatility

There are two dimensions to consider with natural gas price volatility, the operational dimension and the political or strategic dimension. The operational dimension is to handle variations in demand and commercial storage. The political, or strategic, dimension is linked to the possibility of major breakdowns in production or infrastructure resulting from political causes. The nature of the natural gas market is similar to other competitive commodity markets: prices reflect the ability of supply to meet demand at any one time. Like any other commodity, the price of natural gas is largely a function of demand and the supply of the product.

NUCLEAR GENERATION

Rising concern over greenhouse gases from coal and natural gas power plants make nuclear power the third most widely used electricity generation technology. Since nuclear power does not rely on fossil fuels, it does not produce GHG emissions. This characteristic makes nuclear power an important option for reducing GHG emissions in the future. In 2002, nuclear power provided approximately 17 percent of electricity worldwide (Massachusetts Institute of Technology, 2003). An MIT study suggests that an increase of nuclear power production capacity by three times the current capacity by the year 2050 will avoid the 1.8 billion tons of carbon emissions expected to be admitted by coal plants over this same amount of time (Massachusetts Institute of Technology, 2003).

This report estimated nuclear power plant capital costs at US$1,500 to $3,000/kW$_e$. Literature suggests that $2000 is a fair estimate, although the complexity of projects leads to unforeseen costs. Electricity prices for nuclear generation range from US$0.03 to 0.06/kWh. (See appendices for average cost calculations). The highest proportion of costs in nuclear electricity generation are the plant construction costs, waste removal costs, and decommissioning costs, all of which are embedded in the price paid by the consumer. The capital costs vary with the design of the power plant, construction methods, labor and management, and regulatory and approval processes. Total investment costs, including provision for decommissioning and interest during construction range from US$2,000 to $2,500 per kWe. For instance, the Energy Information Administration finds "overnight construction costs are predicted to be US$2,044/kWe in 2010 and US$1,906/kWe in 2025, specified in 2001 dollars" (Massachusetts Institute of Technology, 2003). Nuclear power plants are considered a more attractive generation technology due to the reduction of capital cost by 25 percent or more for the next generation of nuclear plants and the relatively cheaper costs of production to that of other non-renewable energies. As mentioned earlier, safety and decommissioning costs are included in the capital costs and are amortized by the plant owner over the lifetime of the facility. This leaves little or no financial liability left behind for future generations (Agency & Development, 2000).

In addition, uranium supplies are abundant and extraction is not as intensive as for coal. The MIT study, *The Future of Nuclear Energy,* concludes current uranium reserves exist to provide fuel to bring 1000 new nuclear reactors online over the next fifty years and support them over the 40-year plant lifetime (Massachusetts Institute of Technology, 2003).

Limitations of Nuclear

The use of nuclear power is not without drawbacks. The contents of the reactor become toxic with harmful radiation over time, which includes the nuclear fuel rods. Periodically, a nuclear reactor will need to schedule refueling. This process results in spent fuel rods, which represent the most common form of nuclear waste (US Nuclear Regulatory Commission, 2005). In the US, spent fuel rods are typically stored in pools of water on-site. After five years in a pool, the material is less radioactive and considered safe enough to move into casks (US Nuclear regulatory Commission, 2008).

If spent fuel rods are not properly stored and the radioactive wastes are exposed, they will emit harmful radiation for thousands of years. This is a sensitive issue in the United States, though less so in other parts of the world. A more permanent solution to nuclear waste storage is necessary. Deep geological storage of nuclear waste is a potential solution to this need for waste storage expansion. The only known deep repository currently in operation is the Waste Isolation Pilot Plant located near Carlsbad, New Mexico (The World Bank Development Prospects Group, 2009).

RENEWABLE GENERATION SOURCES

Renewable electricity generation encompasses a broad and diverse group of technologies. Principle renewable energy sources include solar, wind, geothermal, and hydroelectric. Wave energy has

tremendous potential but is currently in the research and development phase and is not likely to make a major impact on global electricity supply in the near future. Collectively, renewable sources of electricity generation account for 18 percent of total current global electricity generation, with hydroelectric generation comprising 16 percent of that total (International Energy Agency, 2007). Renewable technologies are not finite and emit substantially fewer greenhouse gases per kWh than fossil fuel energy sources, but that can be limited by geographic and biogenic factors (International Energy Agency, 2007).

Table 2: Selected Renewable Capital Costs and Electricity Prices		
	$/kW$_e$	cents/kWh
Hydroelectric	$1,700 - $2,300	< 5
Geothermal	$1,600 - $4,000	4
Wind	$1,700 - $3,400	8 - 13
Photovoltaic	$3,800 - $5700	21 - 33
Concentrated Solar	$4,700	25
(DOE Report #0556 *Electricity Market Module)*		

Overview of Renewable Sources

Solar
Solar electricity generation is subdivided into concentrated solar power (CSP) and photovoltaic (PV) electricity production. In photovoltaic electricity generation, cells are connected together to form solar panels or arrays. A typical solar cell consists of a glass cover on all sides, an anti-reflective layer to maximize absorption of incoming sunlight, a front and back electrode, and the semi-conductor layers where electrons begin and complete their flow. P-type semiconductors contain positive ions, while N-type semiconductors contain negative ions. The positive and negative ions create the conditions necessary for an electrical current to move through a PV cell (GiraSolar Turkey Ltd., 2009).

Wind
Wind energy is a form of solar energy caused by the uneven heating of the atmosphere as warm air rises and cooler air rushes in to replace it. Wind turbines capture kinetic energy and convert it to mechanical energy to generate electricity using a system of moving parts inside a turbine.

The power capacity of wind turbines has increased dramatically from tens of kilowatts (KW) 25 years ago to upwards of 3.6 megawatts (MW) in onshore (land-based) turbines. Rotors vary in length but can be as long as 100 meters. Both horizontal axis and vertical axis turbines are available and efficiency of the rotors and turbines has increased in recent decades (The Economist, 2008). Modern off-shore (sea-based) turbine designs by Clipper Windpower have capacities ranging from 7.5 to 10 MW. Off-shore turbines account for approximately 1 percent of global wind energy production (The Economist, 2008).

Geothermal
In geothermal electricity generation, liquids that have been heated by subterranean magma and the decay of naturally occurring radioactive isotopes are brought to the earth's surface via drilling, with the high pressure steam subsequently used to turn turbines and produce electricity (USGS, 2003). While drilling has previously been geographically limited to locations where the heat is close to the surface, newer technologies are enabling deeper drilling and utility of resources once regarded as only marginal.

Several factors are needed for a geothermal resource to be capable of producing electricity. First, magma must be relatively close to the surface; current technology allows for the utilization of geothermal resources up to a depth of four kilometers (km)(Duffield & Sass, 2003). These locations largely correlate with tectonic plate boundaries, often residing near volcanoes or where earthquakes frequently occur.

Second, there must be significant quantities of water available to transfer the earth's heat and bring it to the surface. The ability for water to reach the surface depends largely upon underground faulting and the porosity of the rock. With greater porosity and permeability, more water is available. Most research and development is focused on developing techniques to extract geothermal resources where temperatures are sufficient but where there are inadequate liquid resources. These resources are known as hot-dry rock, and the technologies being developed to utilize these resources are known as enhanced geothermal systems.

Finally, the geothermal resource must be hot enough. Electrical grade systems typically use liquids between 100 and 150 degrees Celsius, although higher temperature geothermal liquids can be utilized (Duffield & Sass, 2003). Rock characteristics are important as well, as rocks can conduct or diffuse the heat, rendering the resource inefficient.

Hydroelectric
Hydroelectricity is currently the leading renewable energy source used to generate electricity. According to the International Hydropower Association, 16.1 percent of the world's electricity is generated by hydropower (International Hydropower Association, 2005), and one third of all countries rely on hydropower for more than half of their electricity production (Forsund, 2007). Hydroelectricity generation is globally prominent because plants can operate anywhere that suitable waterways are present. Hydroelectricity is generated using three types of hydropower technologies: large-scale dams, small-scale facilities, and pumped storage. Large dams follow the same basic model: falling water flows through a turbine which turns a generator to produce electricity; this requires water levels to be high enough to provide the "drop" needed to generate sufficient water velocity (United States Geological Survey, 2008). Hydroelectric dams follow the same structural model: water is held in the reservoir, directed through the penstock towards the turbine (increasing both the flow and pressure of water) then spinning the generator where electricity is then harnessed in the powerhouse and dispersed via power lines.

Pumped storage, often used as an electricity back-up, is primarily associated with providing electricity during periods of high demand. During low demand hours (often nights and weekends) facilities reverse pump turbines to transfer water from the lower to the upper reservoir. The captured water is then stored at the top of the reservoir (as potential energy) and released when demand becomes high (Tennessee Valley Authority). Pumped storage is currently the only viable technology that stores large quantities of electrical energy, thus making it very attractive to utilities and consumers alike (Bueno & Carta, 2006).

Wave
Wave energy conversion (WEC) is the process of converting the kinetic energy of waves into electricity by utilizing the motion of waves occurring near coastal areas (Nelson, et al., 2008). Wave power, like wind power is also a form of solar energy: Solar radiation causes uneven heating of the atmosphere, creating winds that drive wave formation in open bodies of water (Thorpe, 1999). For capturing this energy potential, three general types of wave electricity production exist: shoreline, near shoreline, and offshore (Whittington, 2002). Shoreline devices are fixed or embedded in the shore, offering easier installation and maintenance, the elimination of deep water moorings and long lengths of underwater electrical cable, and easier grid connections (Thorpe, 1999)(Buigues, Zamora, Mazon, Valverde, & Perez, 2006). However, shoreline wave regimes are much less powerful and therefore have a much smaller power generation potential (Thorpe, 1999). Near shoreline devices are the least developed of the three types of wave power generation and are designed to operate at circa 20-meters depth (Thorpe, 1999)(Whittington, 2002). Offshore wave electricity power generation utilizes the most powerful wave regimes in water depths greater than 40 meters (Thorpe, 1999). This type of wave power generation offers the largest area of suitable regions for operation, greater supply, and "easier calculation of real energy performance" (Thorpe, 1999).

Global installed wave energy power capacity at the beginning of the 21st century was approximately two megawatts (MW), mostly from demonstration projects (EESD, 2002). The potential for wave energy to provide a substantial portion of global electricity demand is high as the global potential has been estimated at more than 2,000 terawatt-hours per year, roughly 10 percent of world electricity

consumption or 75 percent of current United States electricity demand (Buigues, Zamora, Mazon, Valverde, & Perez, 2006) (EESD, 2002) (U.S. Department of Energy, 2006). Currently, there are advanced plans to increase global wave energy production to 15 megawatts in the near future (EESD, 2002).

Benefits and Limitations of Renewables

Principle features of renewable energies are low greenhouse gas emissions per kWh, relatively low environmental impacts and the inexhaustibility of the resources, but they are limited by geographic and biogenic factors. Apart from hydroelectric, most renewable energy sources are also not currently cost competitive with fossil fuels, though wind power will possibly become comparable in the near future. Some renewable generation technologies are also scalable and can be implemented as distributed generation.

Solar
CSP and PV cells replace fossil fuels with sunlight as the heat source in large solar "farms" (Thomas, 2007). Overall, solar power technology is progressing at an unprecedented rate due to environmental pressures and increasing public interest in greenhouse gas mitigation.

Figure 5: World Daily Irradiation (OK Solar, n.d.)

The available solar resource (irradiation) is a determining factor in the performance of a solar power system. Figure 5 shows global variations in irradiation and the potential daily PV energy output in kWh per square meter. Deserts and low-latitude regions receive more irradiation than temperate regions experiencing greater cloud cover. The PV solar radiation for the US is shown in Figure 6.

The global installed capacity of PV systems totaled 9,200 MW by the end of 2007. As shown in Table 3, the five countries with the most total installed capacity in 2007 were Germany, Japan, U.S., Spain, and Italy. The majority of new capacity that came online in 2007 occurred in Germany and Spain. Table 4 shows the global distribution of this new capacity (European Photovoltaic Industry Association, 2008).
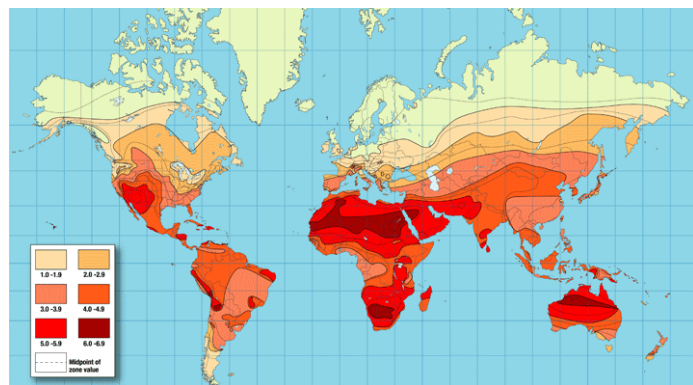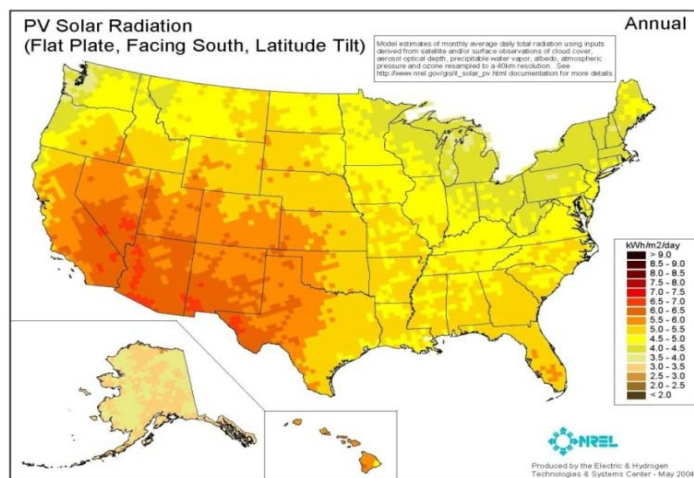

Figure 6: PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)
(National Renewable Energy Laboratory, 2009)

Global CSP capacity in 2007 totaled 457 MW according to calculations done at the Earth Policy Institute (Dorn, 2008). Currently, both the majority of the installed capacity and the majority of plans for new CSP plants are in the United States and Spain.

For distribution, there are three types of PV systems that use solar panels or arrays: distributed grid-connected systems, centralized grid-connected systems, and off-grid systems. Distributed grid-connected

systems include roof-mounted, ground-mounted, and building integrated PV (BIPV). BIPV includes solar roof tiles and facades which serve the double function of building materials and power production and offer a potential net savings on installed costs of solar systems.

Distributed grid-connected systems currently comprise the largest share of the market (European Photovoltaic Industry Association, 2008). Distributed grid-connected systems offer several economic advantages over large-scale centralized PV plants. First, with distributed systems, there are no financial or environmental costs incurred by acquiring the land or preparing the site for construction. Second, transmission losses are minimized with distributed systems since generation occurs at the site of demand. Third, the value of the solar electricity produced by distributed systems is

Table 3: Top 5 PV Markets in 2007, Installed Capacity (MW)	
Germany	3,800
Japan	1,938
US	814
Spain	632
Italy	100
European Photovoltaic Industry Association, 2008)	

higher—this is because the value is equal to the price at which the utility sells the grid electricity which has been replaced, not the cost of generating it (Markvart, 1994). Another benefit of grid-connected systems is the ability to reduce peak demand for conventional electricity, which benefits both the utility (as these systems off-set demand during peak hours), and the consumer (who can off-set electricity costs during peak hours) (European Photovoltaic Industry Association, 2008)

Centralized grid-connected systems are utility-scale power plants. These systems generate bulk power that is distributed through the electricity grid, and typically, the systems are ground-mounted. Conversely, off-grid systems are PV applications for houses, businesses, or entire communities located beyond the reach of the electricity grid. Off-grid systems are stand-alone systems and are found in developed and developing countries alike, though the greatest

Table 4: New Capacity in 2007 (MW)	
Germany	1,100
Spain	512
Japan	230
US	190
Italy	50
Other	310
(European Photovoltaic Industry Association, 2008)	

potential for expansion is in the developing world where about 1.7 billion people lack access to electricity—80 percent of which are in rural areas (European Photovoltaic Industry Association, 2008).

In developed countries, off-grid systems are typically used for electrification in remote areas (such as mountain cabins and other isolated infrastructure). In developing countries, off-grid systems are principally used for rural electrification. Off-grid systems are an option for communities that are dispersed or located at a considerable distance from the grid (European Photovoltaic Industry Association, 2008). The systems can either consist of small systems for individual households or a mini-grid system which can be combined with another fuel source (such as a diesel generator or another renewable technology) and can provide power for a cluster of homes (European Photovoltaic Industry Association, 2008).

Wind
Climate change considerations concerning wind electricity generation are extremely minimal. Wind power uses no fuel during operation and produces no emissions through production of electricity. Air pollution such as particulate matter, mercury, carbon and sulfur dioxide are not produced by wind technologies. Materials used for construction and methods of transportation during the construction phase are the only energy intensive periods of the production process that use fossil fuels and may have adverse effects on climate change (Brune, 2008).

While wind is variable, it is also relatively predictable. Andrew Garrad of Garrad Hassan (a consulting group located in Bristol, England) explains that "wind availability can now be forecast over a 24-hour period with a reasonable degree of accuracy, making it possible to schedule wind power, much like conventional power sources" (The Economist, 2008). If turbine efficiency and electrical grid connections continue to improve, wind energy will become increasingly cost competitive and attractive for larger scale generation.
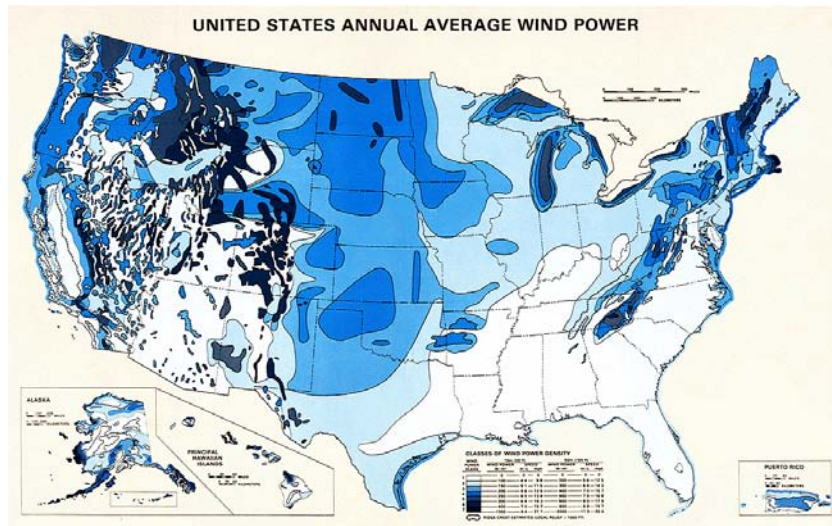

Figure7: Wind power potential within the United States (darker shades of blue represent greater wind power) (National Renewable Energy Laboratory, 2007)

Another advantage to small scale wind electricity generation is the ability to provide power when solar cannot (such as nighttime hours or on cloudy days). Isolated power supply systems using large amounts of wind and other renewable technologies are emerging as technically reliable options for power supply. These systems are generally perceived to have major potential markets as a localized power supply, but they also have considerable potential for use in large utility grids in the developed world (Ackermann, 2005). Figure 7 shows the annual average wind power throughout the US and the location of the densest wind flows.

Geothermal
Geothermal resources are constrained to areas where rock conditions support heat conductivity, and resources are at a depth where they can be extracted. Experience shows that these locations are often located along the so-called "Ring of Fire", near existing faults, and near volcanoes bordering the Pacific Ocean. Current geothermal use is relatively constrained according to available technology and geographic areas which have the necessary rock properties as the ability to extract geothermal energy is largely geographically constrained. The presence of faults, magma bodies, appropriately permeable and porous rock, and high temperature circulating fluids determine feasibility of generation. However, numerous conventional geothermal plants currently produce significant quantities of electricity and some limited potential exists to expand these operations. Presently, the US is the leader in total geothermal electricity production, with a concentration of plants in the western states; producing approximately 3,000 MW of geothermal electricity annually (U.S. Department of Energy, 2008).

Development costs for a typical 20 MW geothermal plant are about US$80 million, with well-field development and surface facilities requiring the most investment (U.S. Department of Energy, 2008). The cost of surface facilities will vary according to the presence of pre-existing infrastructure in the area, particularly transmission infrastructure. In addition to surface facilities, permitting, compliance, and environmental regulations in an area will impact other development costs.

Unlike coal and natural gas plants, geothermal does not rely on a constant incoming source of fuel. Therefore, operation costs are much lower for routine equipment maintenance, parts replacement,

upgrade, and administrative expenses which are typically around US$15 per MW hour (U.S. Department of Energy, 2008). Figure 8 shows the range of geothermal potential for the US
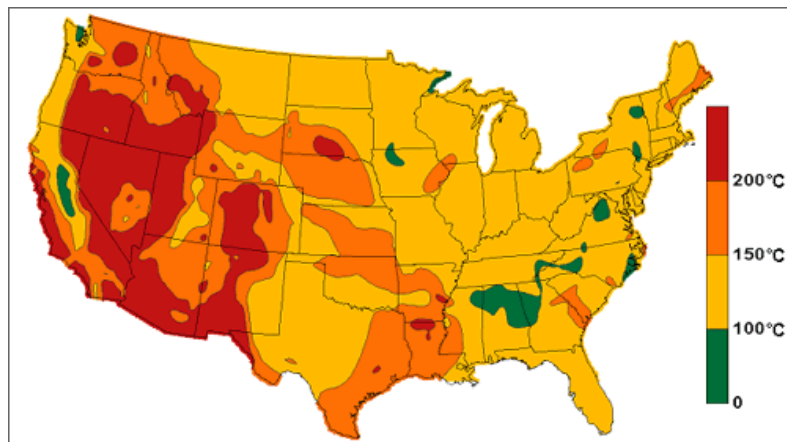

Figure 8: Geothermal potential within the United States (US Department of Energy, 2006)

Hydroelectric

Hydroelectricity provides numerous economic advantages when compared to many other electricity generating technologies. Benefits include dependability, proven technology, high efficiency, low operating and maintenance costs, and the ability to adjust to load changes. Since hydropower facilities with reservoirs offer flexibility and storage capabilities, hydroelectricity can easily respond to unpredictable demand and meet base load requirements. Thus, hydropower provides efficient and low-cost generation when compared to alternate forms of renewable electricity technologies. Furthermore, hydropower is typically a domestic resource, providing greater stability to countries that otherwise rely on international markets to price alternate forms of electricity production. The primary economic disadvantage of hydropower is its high capital costs, although many alternative electricity technologies also require high initial costs. It is important to note that the economic feasibility varies depending on the type of hydroelectricity generated; generation feasibility and costs depend significantly on the size and type of production (International Energy Agency, 2005) (International Hydropower Association, 2005). Concerns over environmental degradation and the toxicity of siltation also need to be considered.

Current fixed costs of large-scale hydroelectricity fluctuate due to site-specific construction costs. According to a study of US hydroelectric facilities with an average size of 31 MW, the initial capital cost ranged from US$1700 to 2300 per kWh. Due to the fact that water is typically a domestic resource, hydroelectricity is a relatively inexpensive way of generating electricity. The cost of producing hydroelectricity varies between plants, primarily depending on the size of the installation. Due to economies of scale, large plants with multiple generators are generally less expensive to operate and maintain, thus producing a cheaper cost per kilowatt of electricity. According to the Idaho National Laboratory, hydroelectricity costs on average 0.7 cents per kWh (0.3 cents per kWh for maintenance and 0.4 cents per kWh incurred by operating costs) (Idaho National Laboratory, 2005).

Wave

Wave energy systems entail a large capital investment and generating costs that are still high when compared to more traditional forms of energy (EESD, 2002). Costs are also highly dependent on numerous factors: system design, wave energy power, water depth, transmission distances, and ocean floor characteristics (U.S. Department of the Interior, 2006). Cost estimates resulting from the "first commercial-scale facilities in the California, Hawaii, Oregon, and Massachusetts offshore regions with relatively high wave energy" ranged from US$0.09 to US$0.11 per kWh, with tax incentives applied, and capital investment costs ranged from US$4,000 to US$15,000 per kilowatt generating capacity (U.S. Department of the Interior, 2006). Another study indicated current costs ranging from US$0.10 to US$0.30 per kWh (Thorpe, 1999).
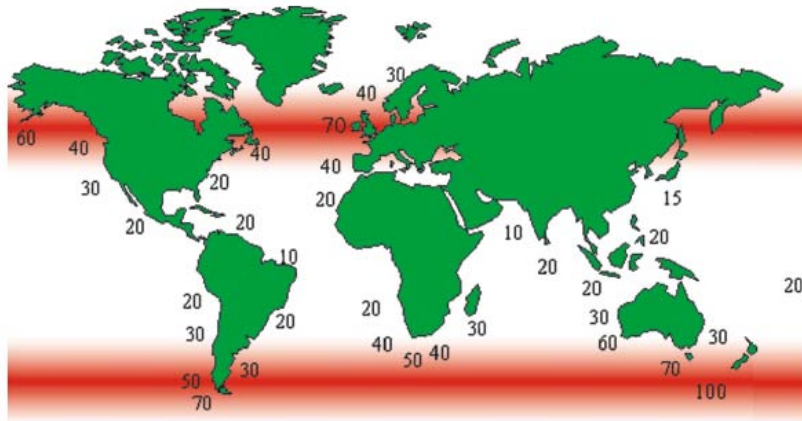
Figure 9: Global wave energy resources in kWh of crest length (EESD, 2002)

Figure 9 shows global wave energy resources in kWh of crest length across the world. Wave energy is economically viable at more than 15-20 kWh of crest length.

DISTRIBUTION SYSTEM TODAY

The system of transmission, distribution, and storage technologies, collectively referred to as "the grid," is the infrastructural link between electricity generation and demand. Like a hub and spoke system, electricity is generated at central power plants then transmitted over great distances to customers. Given the physical limitations of the grid to deliver electricity, over its 130 years of development, the grid has evolved into an inherently capital intensive and relatively rigid infrastructure network with respect to temporal and geographic flexibility. These characteristics pose an optimization problem of how to physically engineer the best means of allocating electricity over space and time, to when and where it is demanded (Kirschen & Strbac, 2004). Dynamic economic and political contexts add a layer of complexity to the optimized delivery of electricity, resulting in inefficiencies like congestion, and unreliability such as electric service interruptions. The challenge of the future of the electric grid is to overcome these barriers to create the most efficient and reliable delivery of least-cost electricity.

ELECTRIC GRID

The mechanics of moving electricity from the generation site to the load center involves several steps through a networked transmission and distribution system. Power plants generate AC electricity that is then stepped up in voltage by a transformer for transmission. High voltage AC carries electricity through aluminum wires suspended by steel towers, the principal physical components of the transmission system (Molberg, 2007). At substations, the high voltage AC electricity is stepped down to lower voltage levels by a second transformer for delivery over distribution networks to consumers. Transmission lines carry electricity to the wholesale market, whereas distribution lines move electricity to the retail market where it is sold to consumers.

The efficiency of electricity delivery is minimized by the loss of electric energy over transmission and distribution lines, and by the temporal flexibility of when generated electricity is used. Holding demand constant, an increase in the engineered efficiency of transmission and distribution lines allows for fewer resources to be consumed during generation to deliver the same amount of electricity. This minimizes associated negative externalities (Baxter, 2006).

Grid Challenges

The electric grid is not a perfectly operating system. Recent blackouts and brownouts in the US and Western Europe demonstrate that the grid is not immune to technological and operational challenges. Brown and Sedano note that the grid may develop physical limits, sag and safety limits, contingency failures, transformer limits and congestion problems (2004):

- Physical limits: High voltage AC, used in transmission can experience electron collision. This results in resistance along the line, which produces heat. Too much heat can result in electrical fires.
- Sag and Safety Limits: An increase in wire temperature will cause a line to sag. These lines may be disabled by trees or other tall objects near the lines.
- Contingencies: System operators often leave a percentage of the transmission line open in case of an emergency where more electricity is needed. If a large power line is disabled, transmission operators should monitor the shift of the electric current. The shift occurs at the speed of light and the system operator must ensure that none of the contingency lines are overloaded when an electrical shift occurs.
- Limits on Transformers: The role of transformers, as was previously discussed, is to step up or step down electrical current. This process releases a large amount of heat and a transformer will fail if the internal oil coolers do not keep the transformer within operating temperature limits (Brown & Sedano, 2004).
- Congestion: Congestion occurs when physical, electrical, or operational limitations restrict the flow of electricity the desired level (US Department of Energy, 2006).

To provide prospective, the Baxter report estimates electricity reliability issues and interruption cost the US economy US$119 to US$180 billion annually (Baxter, 2006), while a report from the Lawrence Berkley National Laboratory reported the cost of interruptions to electricity consumers to be an estimated US$80 billion annually (LaCommare & Eto, 2006). In addition, these costs are not equally distributed by sector. A Pacific Northwest National Laboratory report calculated the costs of electricity interruption to the transportation sector is US$16.42/kWh, the industrial sector is US$13.93/kWh, the commercial sector is US$12.87/kWh, and for residential customers it is US$0.15/kWh(Balducci, Roop, Schienbein, DeSteese, & Weimar, 2002).

Policy Challenges

One of the main challenges to the grid has come from deregulation. In the US, Federal Energy Regulatory Commission Order 888 decoupled electricity transmission and generation businesses and allowed open-access to transmission lines to independent utilities. According to Lerner, decoupling created problems that effect grid reliability and efficiency because:

- Multiple sources adding electricity to transmission lines makes it harder to predict and control for power shifts.
- Decoupling removes the incentive for generators to invest in building more transmission lines.
- Competition between utilities results in predictive data needed to determine system stress and energy flows is treated as competitive information (US Department of Energy, 2006).

Currently, generation utilities often build plants and wheel into existing transmission lines. This creates an overload of supply with inadequate grid support to move the electricity, leaving the system congestible and susceptible to unanticipated generating capacity loss and fluctuations in power quality (Lerner, 2003). Blackouts, brownouts, and other disturbances in the delivery of electricity are the symptoms of an unreliable grid, which damages productivity and incurs significant aggregate damages on a global population increasingly dependent on electric energy. By increasing the reliability of the grid through improvements to transmission, distribution, and storage, these damages can be avoided.

Electricity transmission and distribution also faces efficiency and reliability challenges. Growth in electricity demand has stressed transmission systems. Environmental concerns have led to a push for

renewable energy, which "translates into more generation spread on the transmission system located at some of its weakest points" (Wolf, 2007). New technologies, such as plug-in hybrid vehicles, will continue to stress grid systems. To meet these needs, utilities and/or governments will have to undertake drastic investments in transmission and distribution systems to increase capacity and accommodate growing demand (Chupka, 2008).

SIDE NOTE: ENERGY STORAGE

Depending on the desired application, energy storage can be viewed as a resource for generation, transmission, distribution, end-users, or any combination of the above (US Department of Energy, 2008). Increasing interest in and development of improved storage technologies over the next 50 years will be mainly driven by four trends: 1) Economic incentive to minimize the cost of providing electricity; 2) Growing dependence on reliable electric service to support information storage, communication, and commerce; 3) Increased public resistance to the construction of and decreased utility incentive to invest in expansive transmission infrastructure; and 4) Growing demand for intermittent and distributed renewable energy generation technologies such as wind and solar.

Although there is a broad spectrum of energy storage applications, they can be generalized into three categories: Bulk Energy Storage (BES), Power Quality and Bridging (PQB), and Energy Management (EM) systems. For simplicity, BES systems are applied at the wholesale (transmission) level while the smaller scale energy storage of PQB and EM systems are applied at the retail (distribution and end-use) level. However, in practice there is significant overlap in the range of application suitable for each storage technology.

Bulk Energy Storage: BES systems are applied for load leveling, reserve capacity, and coupling with intermittent renewable generation. The function of these systems is to reduce the time-dependence of electricity generation and demand to increase the system-wide efficiency of electricity delivery. When BES is to be employed, the main consideration is the magnitude of storage (hundreds to thousands of megawatts) that can be economically achieved at a given site (Baxter, 2006). To optimize the decoupling of generation and demand, BES systems in general must be designed to cycle with seasonal and daily demand, ramp-up to full power in minutes, and be able to absorb intermittent electric energy

Power Quality and Bridging: PQB systems are applied to regulate frequency and voltage fluctuations and to bridge outages for durations of seconds to minutes until either auxiliary generation or storage can be brought online (Baxter, 2006). The function of a PQB system is to mitigate damages caused by small fluctuations and interruptions in the quality of electricity provided over the grid (Baxter, 2006, p. 21).

Energy Management Systems: EM systems are applied for small-scale commodity arbitrage allowing for efficient time-of-use electricity cost management (Eyer, Iannucci, & Corey, 2004). Through energy management flexibility, the function of an EM system is to store energy and avoid peak-electricity costs for end-users or to defer transmission and distribution expansion for utilities (Baxter, 2006, p. 168).

Increased Use of Renewable Generation Technologies

"It is generally accepted that no more than 20 percent of a region's demand can be provided by intermittent renewable generation technologies without energy storage" (Denholm & Kulcinski, Life Cycle Energy Requirements and Greenhouse Gas Emissions from Large Scale Energy Storage Systems, 2004). Electric energy storage, developed decades ago to provide the benefits of temporal flexibility to base-load generation, is currently undergoing a revival by promoters of renewable generation technologies, especially wind power. Although storage for the increased use of solar has been discussed, emphasis has been placed on wind power for its off-peak production cycle and lower marginal cost (Cavallo, 2007). The efficiency and economic attractiveness of distributed renewable energy generation applications, especially off-grid systems, are highly dependent on the energy storage system.

Chapter II: Drivers of Change

POPULATION GROWTH

World population growth and increasing per capita incomes, particularly in developing nations, will be the major drivers of world electricity demand in the coming years. This has been the case over the last few decades and is expected to continue. The world population reached 6.7 billion in 2008 alone, according to US Census Bureau estimates. Population growth, especially at this scale, will have serious implications for the demand for electricity and resources used in generating electricity.

By 2030, projections indicate that the global population could reach 8 billion, representing an average annual increase of 60 million people. In a high growth scenario, world population could reach 10.2 billion as soon as 2050. The vast majority of growth, approximately 97 percent, will occur in the developing world (The World Bank Development Prospects Group, 2007). While Western Europe and Japan will likely experience declining populations, and other developed countries may only grow due to migration (The World Bank Development Prospects Group, 2007), developing countries will experience significant population growth. The majority of this growth will be concentrated in East and South Asia.
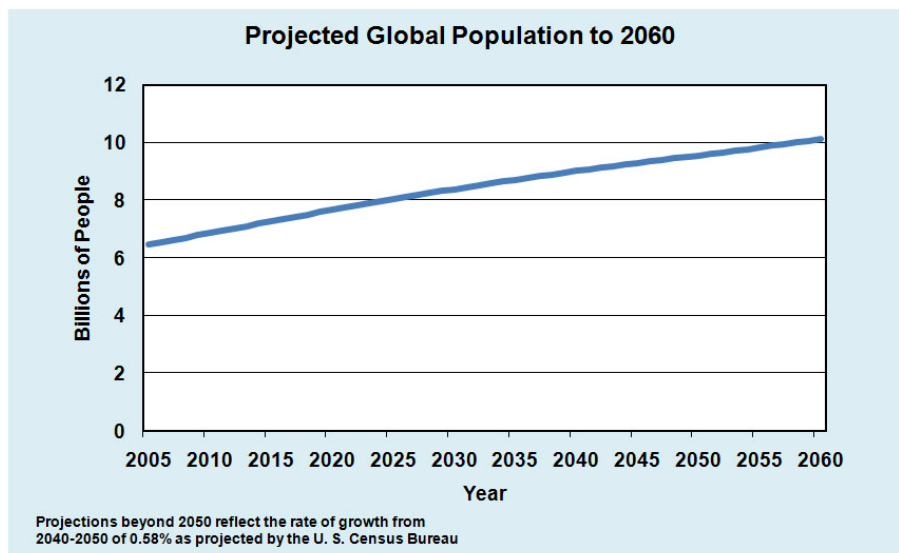

Figure 10: Projected Global Population to 2060

The most rapid growth in energy demand from 2005 to 2030 is projected for nations outside the Organization for Economic Cooperation and Development (non-OECD nations) (Energy Information Administration, 2008). The World Bank suggests 97 percent of population growth will be in the developing world, and developed countries will likely only grow due to migration (The World Bank Development Prospects Group, 2007). Moreover, since much of the population and per capita income growth already occurred in the developing world, a good portion of recent growth in demand for electricity has come from developing regions, in particular East Asia and China (Energy Information Administration, 2008). Overall, demand in Asia has increased more rapidly than the rest of the world since the mid-1960s, and this trend is expected to continue (Ishiguro & Akiyama, 1995).

Nearly all of the predicted population growth is expected to come from middle income and low income countries, with the highest growth rates established in low income countries. It is estimated that by 2035, the population in low-income countries will reach and surpass the number of people in middle-income countries (The World Bank Development Prospects Group, 2007). Figure 11 illustrates this growth.
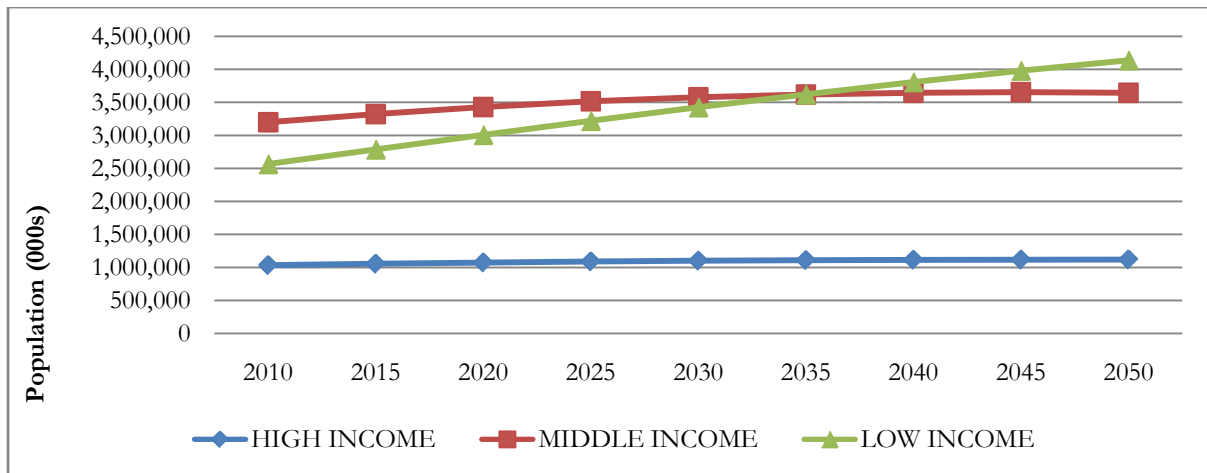
Figure 4: World population in low-income countries will reach and surpass the number of people in middle-income countries. (World Bank Economic Prospects, 2007)

As previously mentioned, the greatest increase in electricity demand will come from the non-OECD countries of the world. The 2006 EIA outlook predicts that the non-OECD countries will account for 71 percent of the net global growth out to 2030 (Energy Information Administration, 2006). This is not surprising, as industrialization in developing nations requires electricity.

ECONOMIC GROWTH

As noted by the EIA's Annual Energy Outlook 2008 with Projections to 2030, electricity sales are heavily influenced by economic growth (Administration, 2008). This can be seen by comparing the EIA's 2008 high and low growth cases. In 2008 the EIA estimated a 39 percent swell in electricity sales, increasing to 5,089 billion kWh under the high growth scenario in 2030, compared to an only 18 percent increase to 4,319 billion kWh under the low growth scenario in the same year.

While global population grows, per capita income and living standards will also rise. Incomes will likely increase more rapidly per year over the next 30 years than they increased in the past 25 years (The World Bank Development Prospects Group, 2007). Overall, global per capita income is expected to grow on average by two percent annually; however, per capita income growth will vary between regions and countries. The World Bank Development Prospects Group (2007) projects that over the next few decades global per capita incomes in developing countries will increase on average by 3.1 percent per year; this is significantly higher than the 2.1 percent increase developing countries experience in the 1980s and 1990s. Chinese incomes, in particular, are expected to comprise 42 percent of developing world incomes by 2030, but currently represent only 19 percent. By contrast, per capita incomes in developed countries are expected to increase by only 1.9 percent per year (The World Bank Development Prospects Group, 2007).

This growth will contribute to the emergence of a larger global middle class, and in turn a new demand for services and products that did not exist before. The World Bank (2007) calculates that approximately 1.2 billion people who live in developing nations will belong to the global middle class by 2030. Current numbers show that only 400 million people in the developing world belonged to this category in 2005 (The World Bank Development Prospects Group, 2007). According to these projections the number of people living in the most impoverished conditions will likely decline. For example, currently 1.1 billion people survive on less than US$1 per day, which is a World Bank measure for purchasing power parity (PPP) across countries or areas (The World Bank Group, 2004). By 2030, projections indicate that this number will have decreased to 550 million people, only half the number living in extreme poverty today (The World Bank Development Prospects Group, 2007).

Analysts sometimes assume that economic downturns causing short-term variation cancel out in long-term demand trends (Gotham, 2009). However, the current global economic situation could have a significant impact on long-term global electricity demand if long-term growth rates are affected, or if energy-use paradigms shift. The World Bank's March 2009 report on how developing countries are weathering the global crisis indicates that the 2009 global GDP is expected to decline "for the first time since World War II, with growth at least 5 percentage points below potential" (The World Bank, 2009, p. 1). Eastern European and Central Asian countries, and other producers of capital goods, have been hit especially hard recently due to losses in global industrial production. The World Bank predicts that the financial crisis will have a long-term impact on developing nations, with weaker investment, slower future growth and a steep increase in debt issuance from high-income countries that can crowd out many private and public developing country debt issuers (The World Bank, 2009).
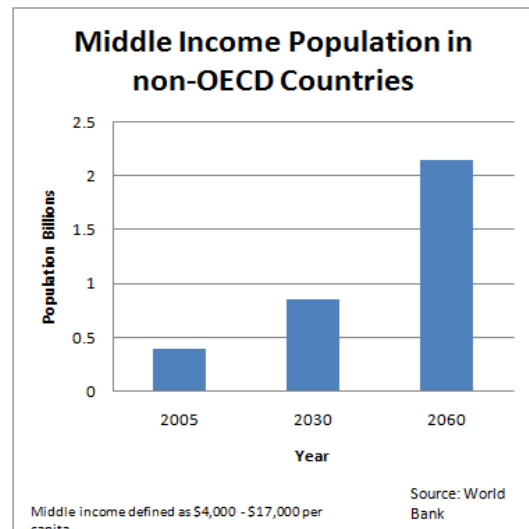

Figure 12: Middle Income in non-OECD Countries (World Bank)

FUTURE CONSUMPTION OF ELECTRICITY

Over the next 50 years we estimate that global electricity consumption will increase 350 percent from about 20 quadrillion kWh to just under 70 quadrillion kWh per year, as shown in figure 13. This assumes a constant annual growth rate of 2.7 percent and is consistent with other long term projections (Kruger 2008). This expanding population growth will lead to an annual rate of demand growth in the non-OECD countries of 3.9 percent.
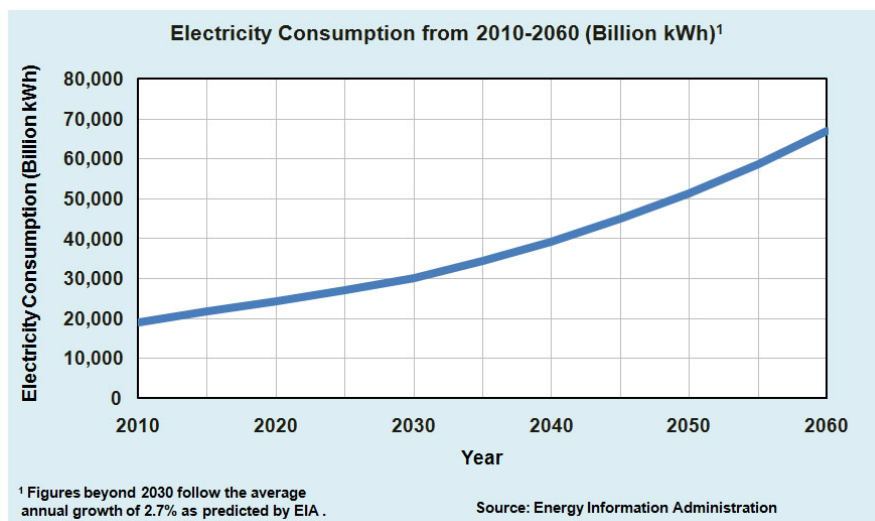
Figure 13: Predicted 350 percent increase in global electricity consumption

The EIA notes, "Asia has the highest growth rate at 4.7 percent per year, followed by Central and South America at 3.7 percent, the Middle East at 3.0 percent, Africa at 2.9 percent, and non-OECD Europe and Eurasia at 2.8 percent" (Energy Information Administration, 2006). This amounts to nearly a tripling of the net electricity consumption of non-OECD countries from the 2003 base numbers. By 2030, non-

OECD countries will be consuming 56 percent of the world's electricity, up from 40 percent in 2003 (Energy Information Administration, 2006).

While the EIA expects the world consumption for electricity to increase steadily through 2060, the actual rate of the increase in consumption may accelerate or decelerate. This is dependent on a number of factors: the receptiveness of electrically powered vehicles, the fallibility of energy forecasting models, the price elasticity of demand for electricity, and the negative effect of climate change mitigation on electricity consumption.

Factors like the favorability and wide distribution of electrically powered or "plug-in" hybrid automobiles will necessarily expand the residential consumption for electricity. Projections on the gradual replacement of fossil fuels with hydrogen in the generation of electricity anticipate the world supply of automobiles to increase from 900 million to 1.5 billion from 2010-2050 and the consumption of electricity to increase by 10 kWh per year (Kruger, 2005). The US expects to have two million automobiles by 2030, according to the Energy Information Administration (Administration, Annual Energy Outlook 2008 with Projections to 2030 , 2008)[See sidebar]. In addition, hybrid automobiles will require an additional 3-4 hours in order to recharge, thereby increasing the observed "off-peak" demand (Agency, 2008).

LIMITATIONS OF PROJECTIONS

Observed changes in the rate of demand growth may also relate to the accuracy of the projections themselves and possible biases in the estimates. Based on an empirical study of the EIA's forecasts in the energy market, it was found that under- and over-estimation occurred quite regularly, the demand for residential and commercial electricity was usually underestimated, and the demand for renewable resources for electricity generation experienced "the greatest upward bias overall" (Fischer, Herrnstadt, and Morgenstern 2008). In addition, this tendency worsens as the time horizon on the projection lengthens (Fischer, Herrnstadt, and Morgenstern 2008). In general, the EIA tends to "under-predict" energy prices which ultimately leads to an "over-projection" – and hence unreliability – of the EIA's energy demand models (Fischer, Herrnstadt, and Morgenstern 2008). Although it is usually advantageous for projections to be more conservative in order to account for uncertainty, even conservative estimates can hinder accurate forecasts of changes in electricity demand.

Residential Demand and the Electric Car

An important variable in predicting demand includes the use of "electric drive vehicles," a term coined by UC Davis professor Dan Sperling. This refers to battery electric vehicles, plug-in hybrids, gasoline hybrids, and fuel cell electric vehicles. With respect to plug-in hybrids, residential electricity demand could substantially increase. According to the Energy Information Agency, US, sales of plug-in electric and hybrid electric cars is expected to reach 2 million cars by 2030 (Agency, 2008). In addition, 3-4 hour recharge times are required with current technologies, suggesting residents will plug cars into home outlets at night, causing upward shifts in off-peak demand curves.

A 2006 US Department study found that "there is enough "off-peak" electrical capacity to power 84 percent of the country's 220 million vehicles if they were so-called "plug-in" hybrids" (US Department of Energy, 2006). However, technological improvements are already targeting charge time reductions and rapid charging at home or away is a possibility.

Key electric car selling points include obvious social benefits associated with minimal emissions and reduced noise compared to traditional automobiles. However, electric cars do not escape basic marketing and consumer demand principles. Current electric cars are expensive, dangerous in collisions with larger petrol fueled cars, and need technology improvements in charging and travel distance. Further, emissions gains from mobile sources are lost to an unknown degree to coal fueled or other generation facilities. Electric cars could end up contributing worse to climate change than petrol-fueled cars if large generators are dirty. However, emission regulation could also prove easier through consolidation from many mobiles sources to a few large point sources.

Energy conservation is another major driver of change. Applications of demand side management and the Smart Grid will lead to the more efficient end-use of electric energy; however, the impact of conservation efforts on the future of electricity is relatively small compared to the impact of demand growth, climate change, and resource availability.

DEMAND SIDE MANAGEMENT

If demand moves to the capacity limit, the price of supplying a given unit of electricity would increase drastically. This characteristic of the electricity market is a significant obstacle to the accurate prediction of electricity demand in the future. Moreover, it also encourages the inefficient usage of electricity which could affect its availability in the longer run. In order to address the issues, Demand Side Management (DSM) is utilized. Demand Side Management refers to:

> "the planning, implementation, and monitoring of utility activities designed to encourage consumers to modify patterns of electricity usage, including the timing and level of electricity demand. It refers to only energy and load-shape modifying activities that are undertaken in response to utility-administered programs. It does not refer to energy and load-shaped changes arising from the normal operation of the marketplace or from government-mandated energy-efficiency standards. Demand-Side Management covers the complete range of load-shape objectives, including strategic conservation and load management, as well as strategic load growth" (Energy Information Administration).

Under the umbrella of DSM, the notion of inducing demand response is among the key activities in improving the efficiency of electricity market by provoking a demand response in consumers. As a result, changes in cost of production or other related costs would be used to predict or gauge market changes more accurately. There are many forms of DSM that could create this desirable change in the market. However, only the prices consumers see in every sector have the most impact on consumption behaviors. Therefore, the discussion about DSM will focus on the pricing schemes imposed on the consumers.

The implementation of DSM can bring benefits for both consumers and producers in the electricity market, including:

- Reduced customer peak and overall demand
- Improved electricity grid reliability
- Balance in the electric grid through increased efficiency
- Creation of efficiency in one of the most capital-intensive sectors.
- Managing electricity costs
- Conservation through both behavioral and operational changes
- Load management
- Fuel switching
- Distributed energy
- Increased customer choice and customer risk management opportunities
- Potential environmental benefits
- Providing systems that encourage load shifting or load shedding during times when the electric grid is near its capacity or electric power prices are high (Demand Side Management Solutions) (Violette, Freeman, & Neil, 2006).

SMART GRID

The concept of a "Smart Grid" has become synonymous with the future of reliable and efficient electricity throughout the world. The Smart Grid envisions an overhaul of the current electric grid and offers technological improvements in distribution. With the Smart Grid, a consumer can choose their energy consumption using a home-operated interface. In brief, the Smart Grid proposes a complete rethinking and retooling of the current grid system in order to make electricity delivery more reliable, conducive to renewable sources of energy, market based, and adaptive to future demands. The Smart Grid is theoretical in terms of application; however, test cases that have experimented with this innovative way of rethinking electricity.

The US Department of Energy has designated seven objectives for the Smart Grid that would guide its implementation: self heals, motivates and includes the customer, resists attack, provides power quality, accommodates generation and storage needs, enables market participation, and optimizes assets and operates efficiently (U.S. Department of Energy - Energy Efficiency and Renewable Energy, 2007).

The following five key technology areas are identified by the Department of Energy as essential to achieving the Smart Grid's principal objectives. It is important to note that no single area is considered "complete" or ready for full implementation of the Smart Grid. It is better to think of this list as a blueprint for Smart Grid technology. The Department of Energy describes their functions below (National Energy Technology Laboratory, 2007):

- Integrated Communications: "High-speed, fully integrated, two-way communication technologies will make the modern grid a dynamic, interactive "mega-infrastructure" for real-time information and power exchange"
- Sensing and Measurement: "These technologies will enhance power system measurements and enable the transformation of data into information. They evaluate the health of equipment and the integrity of the grid and support advanced protective relaying, they eliminate meter estimation and prevent energy theft"
- Advanced Components: "Advance components play an active role in determining the grid's behavior. The next generation of these power system devices will apply the latest research in materials, superconductivity, energy storage, power electronics, and microelectronics"
- Advanced Control Methods: "New methods will be applied to monitor essential components, enabling rapid diagnosis and timely, appropriate response to any event. They will also support market pricing and enhance asset management and efficient operations"
- Improved Interfaces and Decision Support: This will enable the Smart Grid to implement "wide, seamless, real-time use of applications and tools that enable grid operators and manager to make decisions quickly"

According to the Office of Electricity Delivery and Energy Reliability, if implemented the Smart Grid will reduce blackouts, be based on a market driven system where consumer interaction with electricity producer occurs in real time, includes all energy production capabilities, and will completely change our paradigm of the grid system of power distribution (DOE, 2009).

NON-RENEWABLE FUELS

While coal, natural gas and uranium are finite resources; they are currently abundant and will remain so for the next 50 years.

Coal is the lowest cost nonrenewable fuel source for electricity generation. In addition to its low cost, it is abundant in both developed and developing countries. "Although coal deposits are widely distributed, 76 percent of the world's recoverable reserves are located in five countries: the United States (28 percent), Russia (19 percent), China (14 percent), Australia (9 percent) and India (7 percent)" (Energy Information Administration, 2008). Global coal reserves total 930 billion tons (Energy Information Administration, 2008). According to the EIA 2008 Outlook's projections, the current reserves-to-production ratio is estimated at 143 years (Energy Information Administration, 2008).

Natural gas is the second lowest cost nonrenewable fuel source for electricity generation. As of January 1, 2008, proved worldwide reserves measure 6,186 trillion cubic feet. Natural gas reserves are geographically dispersed, spanning across all continents with the exception of Antarctica. On a global scale, the reserves-to-production ratio for natural gas is estimated at 63 years. The majority of reserves are found in the Middle East and Eurasia (Administration, US Energy Information Administration/Short-Term Energy Outlook , January 2009).

Conventional uranium reserves that can be mined for under the benchmark of US$130 per kg measure 5.5 million tons (IAEA, 2001). The lifespan of proved uranium reserves depends on reactor type. For current once-through fuel cycle with light water reactor, uranium reserves are expected to have a lifespan of 85 years using the base year of 2005. For pure fast reactor fuel cycle with recycling, uranium reserves are projected to last 5,000 to 6,000 years (Sokolov, 2006).

Nonetheless, the dominant, nonrenewable fuel sources for electricity generation are not expected to change within the next 50 years.

AVAILABILITY OF FRESH WATER

Water is a necessary input to generate electricity and is required for various purposes and in varying amounts according to the generation technology. For example, in the generation of electricity from coal, water is required for mining, washing, fuel conversion and cooling processes. In the US, electricity generation by thermoelectric plants accounts for 39 percent of all freshwater withdrawals in the country, making it second only to agriculture in terms of freshwater use. Power plants that use coal to generate electricity, thermoelectric power plants, require large amounts of water, with the majority of this water used for cooling processes (NETL/DOE, 2008).

Table 5 presents water consumption by generation technology. The table illustrates that solar thermal consumes the most amount of water to generate a kWh of electricity, followed by nuclear and then coal. Renewable technologies such as photovoltaics and wind consume the least amount of water.

Table 5: Water Consumption by Generation Technology	
Technology	Gallons/kwh
Coal	0.49
Natural Gas Combined Cycle	0.25
Nuclear	0.62
IGCC (Wet)	0.55
IGCC (dry)	0.175
Wind	0.001
Geothermal (fresh water)	0.44
Solar Thermal	0.79
Photovoltaic	0.03
(Torcellini, Long, and Judkoff, 2003; Wiley, 2007; Virginia Water Resource Center, 2008)	

The availability of freshwater in an area influences the type of technology employed to generate electricity. In the future, population growth, economic growth and climate change will impact local and regional water resources (United Nations, 2009). In particular, climate change will cause increased stress on freshwater supplies in some areas and more abundant supplies in others. Water availability is projected to decrease by 10 to 30 percent in some dry regions at mid-latitudes and in the dry tropics due to reduced precipitation and higher rates of evapotranspiration, while high latitude and some wet tropical areas will see an increase of 10 to 40 percent in water availability as a result of increased runoff. Climate change is projected to exacerbate current stresses on water supply in areas suffering from drought and many semi-arid areas, such as the western United States, southern Africa, the Mediterranean Basin and north-eastern Brazil. In Asia, melting glaciers in the Himalayas are projected to affect water resources within the next twenty to thirty years, which will include decreased runoff and water flow in rivers. Overall, freshwater supply in the region will decrease, and water resources will be further stressed due to increasing demand stemming from both population growth and economic growth. Reduced water supply and hydropower potential are anticipated in Southern Europe while Central and Eastern Europe will face a reduction in precipitation. As glaciers retreat and precipitation patterns change, Latin America and the Caribbean will also experience reduced water availability (United Nations, 2009).

GENERATION AND DELIVERY INFRASTRUCTURE

Generation Building Costs

The costs associated with the development of generation and transmission infrastructure require large capital investments, and delivery infrastructure is capital-intensive and logistically challenging to expand. Capital costs have risen due to an increase in costs for construction related materials, such as cement, iron, steel, and copper (IEA, 2008). The demand for new generation facilities to produce electricity is one reason costs for construction related materials have increased.

According to the World Bank, the demand for power plant and infrastructure equipment has been higher than manufacturers' ability to supply the resources. This increase in demand has resulted in pricing based on estimates for equipment and services, rather than the actual cost of production. The construction of new generation plants has translated to an increase in demand for raw building materials. For example, from the period of January 2005 to December 2006 price for electric wire and cable increased by 23 percent and power transformers increased by 32 percent (The World Bank, 2008).

Depending on the generation technology, the capital costs associated with the plant construction will vary. For example, the capital cost of a Pulverized Coal (PC) generation facility is reported to be US$1,562 per kW without Carbon Capture technologies. With CCS technology, PC facilities have the highest capital cost at an average of US$2,883 per kW (DOE/NETL, 2007).

Table 6: Capital Costs for Transmission

Transmission Costs

The current grid system faces operational and system stresses. As was discussed in the distribution today section of this analysis, challenges to the grid include blackouts and congestion along transmission lines. Investment in improved electricity transmission is necessary to mitigate these problems, as well as encourage the development of large-scale renewable electricity generation.

Transmission Facility	Capital Cost ($ per mile)
New 345 kV single circuit line	915,000
New 345 kV double circuit line	1,710,000
New 138 kV single circuit line	390,000
New 138 kV double circuit line	540,000
Single circuit underground lines	Approximately 4 times the cost of single circuit lines
Upgrade 69 kV to 138 kV line	400,000

Source: National Council on Electricity Policy, "Electricity Transmission: A Primer," June 2004.

The World Energy Outlook 2008 (WEO) report projects that large-scale investment in infrastructure is needed to meet increased electricity consumption. The report states, "cumulative investments of over

US$26 trillion is needed between 2007 and 2030. The power sector accounts for US$13.6 trillion of the investment, or 52 percent of the total" (International Energy Agency, 2008, p. 5). The WEO also notes that half of its projected investment goes towards maintenance of the current supply capacity systems. According to WEO, by 2030 the majority of the electric infrastructure will need replacement (International Energy Agency, 2008).

The capital costs of transmission lines that use standard Alternating Current (AC) voltage have differing costs compared to High Voltage Direct Current (HVDC) lines. Table 19 provides a snapshot of capital costs for electric transmission lines in the US at various voltage levels. The capital costs associated with HVDC transmission lines are higher compared to AC. The capital costs of an HVDC system are higher then an AC system because more auxiliary equipment is needed. HVDC systems are not economical for loads less than 20 MW or at distances less than 500 km (Rudervall, 2000).

Another issue that must be factored into costs of transmission infrastructure is the use of land. When building new transmission lines, permitting and property right-of-ways influence the location of new grid development. This can lead to increased costs associated with building transmission lines.

CLIMATE CHANGE

Estimates from the Intergovernmental Panel on Climate Change (IPCC) indicate that the average global surface temperature will increase by approximately 1.8 to 4.0 degrees Celsius by the end of this century. Emissions of CO_2 and other greenhouse gases are intensifying from an increase in power usage, transportation, population size, industrialization in developing countries, and living standards. Global climate change will likely lead to changes in major weather patterns, ambient temperature, precipitation, humidity, cloud cover, and wind speed. Such changes in weather parameters will affect energy consumption and demand globally (Parkpoom S. A., 2008).

Increased demand for electricity will result in greater supply, which in turn will result in greater GHG emissions. The National Academies Summit on America's Energy Future reports that, "according to the available evidence, the second half of the 20th century was warmer than any other 50-year period in the last 500 years, and probably in the last 1,300 years" (National Academies Summit on America's Energy Future, 2008). During the 20th century, global and ocean temperatures increased by approximately 0.6 degrees Celsius (National Academies Summit on America's Energy Future, 2008). Population growth, and the inherent changes to the environment that are associated with that growth, have increased CO_2 emissions "from about 300 parts per million in 1900 to about 380 parts per million today" (National Academies Summit on America's Energy Future, 2008).

ELECTRICITY GENERATION AND GREENHOUSE GAS EMISSIONS

By 2030, the electricity industry accounted for almost 45 percent of global energy-related CO_2 emissions. The EIA (2008) reports that world CO_2 emissions will increase from 28.1 billion metric tons in 2005 to 34.3 billion metric tons in 2015 and 42.3 billion metric tons in 2030, with the World Energy Council (WEC) giving similar estimates (World Energy Council, 2007). Climate change will influence individual electricity consumption and political decisions regarding the electric industry.

Weather parameters affect electricity demand, which are observable through present weather trends and electricity consumption trends throughout seasonal, diurnal, and geographic demand variations. Figure 14 is from a study conducted in California, specifically from the cities of San Francisco, Sacramento, Fresno, and Los Angeles. The figure shows average daily energy demand as a function of temperature. This figure illustrates how electricity demand relates to temperature and demonstrates that as temperature increases electricity demand also increases. Furthermore, once the temperature rises above a certain level, electricity demand begins to increase at a faster rate (Franco & Sanstad, 2006).
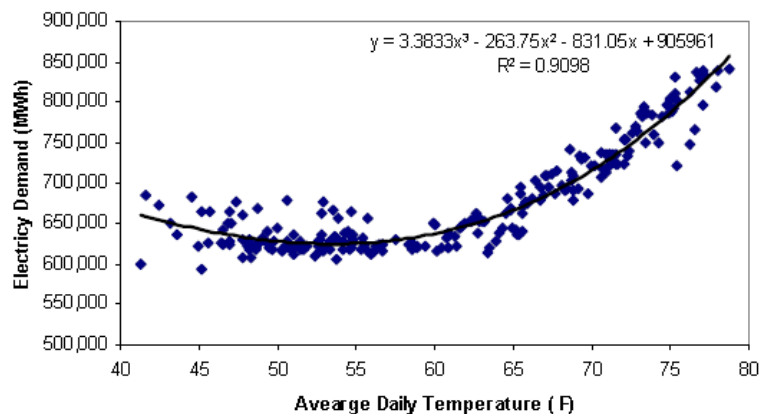
Figure 14: Electricity Demand as a Function of Average Daily Temperature from 2004
(Franco, 2006)

Global Climate Change Trends and Electricity Demand Predictions

Climate parameters influence energy demand, specifically electricity consumption, mainly by affecting how much air conditioning, space heating, water pumping, and refrigeration are used. Analysis of current electricity demand and the trends associated with weather, combined with estimations of weather changes that are likely to occur due to global warming, help to predict how electricity demand will change over time and across different geographic regions and the residential, commercial, and industrial sectors (Parkpoom, 2008).

Many studies analyze the number of heating and cooling days per year. Peak electricity-demand-load-days are of special interest, as these typically occur on the hottest days. For this reason, global warming could have the greatest impact on peak load. If the system is not prepared to handle this increase in peak demand, brownouts and blackouts may result (Parkpoom, 2008).

GREENHOUSE GAS MITIGATION

Government Regulations/Policy

Kyoto Protocol
The Kyoto Protocol is an international agreement that sets compulsory targets for reducing GHG emissions for 37 industrialized countries and the European Community. The Kyoto Protocol was originally adopted on December 11, 1997 and went into force on February 16, 2005. The requisite target level for reduction is an "average of five percent against 1990 levels over the five-year period 2008-2012" (United Nations Framework Convention on Climate Change, 2009). Since the Protocol is binding, signatory countries are committed to meeting the emission reduction levels.

In general, the Protocol places a greater burden on industrialized countries since these countries are the historical source of the majority of GHG emissions (United Nations Framework Convention on Climate Change, 2009). Countries are expected to meet target levels through national measures; however, the Protocol also provides strategies for meeting reduction level, such as emissions trading via carbon markets (Stern, 2005).

European Mitigation Policy
In 2005, the European Union initiated a regional GHG emission trading system known as the EU Emissions Trading Scheme (EU ETS). This scheme included three implementation periods. Phase I took place from 2005-2007, Phase 2 will last from 2008-2012 (with 95 percent of allowances initially

distributed at no cost), and Phase 3 will begin in 2013 (Egenhofer, 2007). Under the EU ETS, each EU country decides on the number of allowances to be dispensed in each time period and submits this National Allocation Plan to the European Commission for approval. These allowances can be purchased and sold by facilities, with banking of allowances allowed only if an equal number are removed from the total allocated in the next phase . The EU ETS is designed to be compatible with and help countries achieve agreements made under the Kyoto Protocol (Legge, 2003).

The feed-in tariff system is another policy option that is widely employed in Europe to provide incentives for electricity generation from renewable sources. Feed-in tariff systems require utilities to purchase renewable electricity at above market rates that are set by the government. In Germany, the utilities are required to purchase electricity produced by newly-installed PV systems at a tariff of €0.35 per kWh to €0.47 per kWh. The tariff is determined by the type and size of the system and also by the year of installation. The additional cost of the solar electricity is spread equally among electricity customers. The feed-in tariff system also includes safeguards to encourage continued PV price reductions. Each year the rate that is offered to customers with newly-installed systems decreases by a certain percentage (the rate a customer is offered is the rate the customer will receive for the duration of the eligibility period, which is 20 years). Prior to 2009, this was set at 5 percent; however, beginning in 2009, the percentage increased to 8 to 10. The decreasing tariff provides the PV industry with an incentive to innovate and cut costs while the steady feed-in rate that customers receive for the duration of their eligibility period allows customers to calculate the return on their PV investment.

In contrast to programs that provide a subsidy in the form of a rebate or tax credit per installed capacity unit to off-set the high initial costs, the feed-in system encourages not only the installation of high quality systems, but also encourages proper operation and maintenance since the feed-in tariff is dependent upon the performance of the system. The customer is encouraged to maximize the power output of the system during the system's lifetime as the customer receives the return on investment with each kWh that is fed into the grid (European Photovoltaic Industry Association & Greenpeace, 2008).

US Energy Policy Acts
The Energy Policy Act of 2005 (EPACT 2005), is an energy plan designed to increase domestic energy production, encourage energy conservation and efficiency, and promote the development and use of renewable and alternative energy sources. The legislation contains numerous provisions covering energy production, conservation, distribution, storage, efficiency, and research. It includes mandatory energy conservation and efficiency standards; creates tax credits for businesses and individuals making energy-efficient improvements; and provides tax incentives and loan guarantees for energy production of various types (Petroleum, 2008).

Lieberman-Warner Climate Security Act of 2008 (S.3036)
The Lieberman-Warner Climate Security Act proposes a federal program with the task of reducing GHG emissions between 2008 and 2050. The bill "establishes a market-driven system of tradable emission allowances and permits the use of domestic offsets and international credits" (Environmental Protection Agency, 2008). The emissions cap outlined in the bill includes producers of GHGs, such as electric power generators, transportation, manufacturing and natural gas sources (Lieberman-Warner Climate Security Act 2008, 2008). In addition, the Act will use the money raised from auctions and set aside emission allowances to fund the development of abatement technology that reduce emissions. Taking into account the potential effects of this bill, GHG emissions are projected to be 56 percent lower than the reference case in 2050. Moreover, according to the EPA, the greatest decrease in CO_2 emissions will occur in the electricity sector (Environmental Protection Agency, 2008).

Carbon Offsets and Abatement Technology

Two mitgation tools to reduce carbon emissions are offsets and abatement technology. Many of the aforementioned policy tools offer a combination of the two reduction strategies. Offsets refer to a reduction in net emissions where the electric generator pays a secondary party to reduce their emissions so the original electricity generator could continue to emit CO_2 while not increasing overall global

emissions. Abatement technology such as Carbon Capture and Storage (CCS) reduces CO_2 emissions at the generation source.
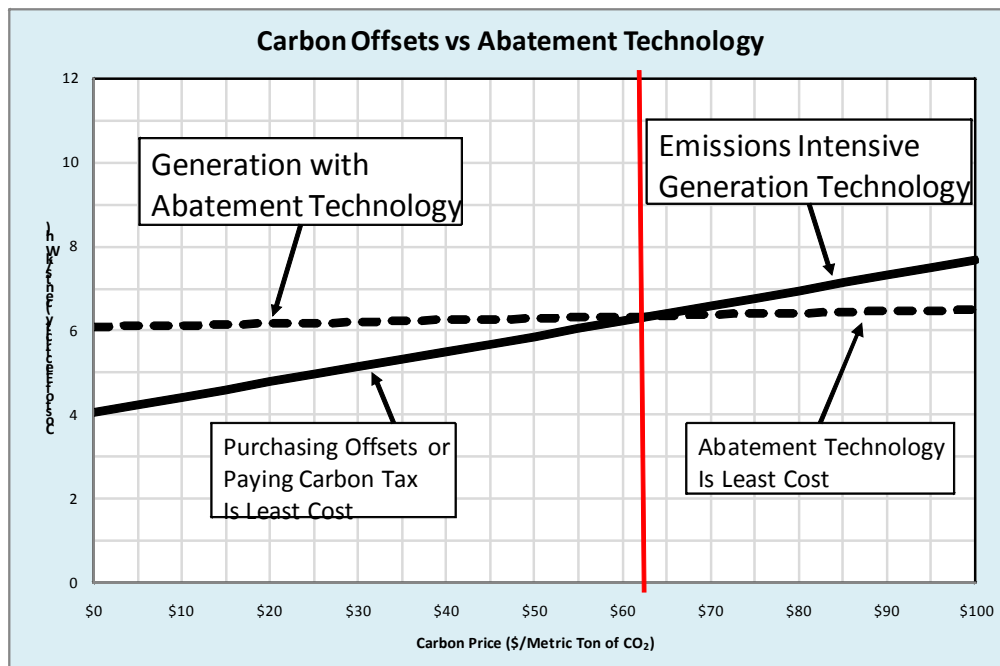

Figure 15: Carbon Offsets vs. Abatement Technology[6]

Both carbon offsets and abatement technology increase the cost of electricity generated from nonrenewable fossil fuel sources. Figure 15 depicts the emissions reduction option that is least cost at different carbon prices per metric ton of CO_2 to generate electricity. If policy tools mandate a reduction of CO_2 emissions, fossil fuel generators will utilize carbon offsets until a price of approximately US$63 per Metric Ton of CO_2. At carbon prices to the right of the red line, abatement technology becomes the least cost alternative to reduce emissions and meet demand for electricity.

Cap and Trade, Carbon Taxes, Government Regulations (maximums)

As the global community recognizes the need for abatement of GHG emissions, policies outlining the best methods for achieving abatement continue to be discussed. In order to reduce emissions at the least cost possible, "a common price signal is required across countries and different sectors of the economy" (Stern, 2005, p. 311). This price should reflect the "marginal damages caused by emissions," and the price should continue to increase over time as the overall level of greenhouse gases increase as well (Stern, 2005, p. 316). Two of the most commonly cited policy tools for achieving emissions reductions are carbon taxes and tradable quotas.

Cap and Trade Emission Reduction Programs
One policy approach to control atmospheric pollution is through the trading of emissions, otherwise known as a cap and trade system. Under this approach, a governing body specifies a limit (cap) on the amount of emissions permitted by particular industries. Covered entities that emit a particular pollutant are required to have an equivalent number of credits for the amount that they release. Those entities emitting more than the amount of credits they hold can purchase additional credits from other participants (Clean Air Markets Division EPA December 2008).

Besides purchasing or applying a currently held allowance to account for emitting a ton of a particular pollutant, a facility may obtain additional credits to meet its obligations by implementing a project that

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[6] Figure generated with information from this report.

reduces emissions elsewhere. According to the Pew Center on Climate Change (Fall 2008), offset projects involving GHGs can provide additional opportunities for mitigation at a reduced cost. Other benefits of incorporating offsets into a cap and trade system are: achieving reductions in an area not currently regulated, providing opportunities for developed countries to assist less developed countries, and providing additional benefits besides the reduction in emissions (e.g. additional wildlife habitat). A GHG offset is defined as one where there is a "reduction, avoidance, destruction, or sequestration of CO_2 or other GHG emissions that: 1) is from a source not covered by an emission reduction requirement; 2) can be measured and quantified; and 3) can be converted into a credit if it meets established eligibility criteria. This credit can then be sold and used by another party to meet its compliance obligation under a cap-and-trade program" (Pew Center for Global Climate Change, Fall 2008).

Although there are benefits to providing offsets in a cap and trade system, there are potential issues with implementation. Actors may delay technological changes, with regulated groups having the ability to implement projects, which provide them with additional credits to meet their emission targets at a cheaper cost than reducing emissions at their own facilities (Pew Center for Global Climate Change, Fall 2008). Another concern is whether approved projects represent real emission reductions. This issue is related to the fact that with project based allowances a company could invest in a project outside of its operating area that will reduce its CO_2 emissions. This does not reduce emission levels at the operation site (Pew Center for Global Climate Change, Fall 2008).

Carbon Taxes
Another policy tool for creating a common carbon price signal is the carbon tax. Carbon taxes are designed to assist in changing consumer behavior and set aside funds to assist in smoothing the transition to a cleaner economy. The most widely discussed proposals are applying either a levy on these fuels across the board or a tax based on their CO_2 emissions (Massachusetts Institute of Technology, 2007). A carbon tax is, in essence, "a tax on the carbon content of fossil fuels" (Watson, Zinyowera, & Moss, 1996). This is similar to a tax on the CO_2 emissions produced from using fossil fuels; however, it is simpler to govern because it provides "greater price predictability" (Stern, 2005, p. 339).

Moreover, carbon taxes are transparent and offer a certain level of political appeal because of the level of transparency. Conversely, economic analysis of the use of a carbon tax sometimes disregard the utility of a carbon tax because of the possibility of opposition to taxes on the part of the public (Massachusetts Institute of Technology, 2007).

Carbon Markets
Carbon markets refer to the buying and selling of emissions permits. The permits are either distributed by a regulatory body or generated by GHG emissions reduction projects. The markets can be divided into two forms, regulatory or voluntary. Voluntary carbon markets represent an interesting mitigation strategy for GHG emissions (Hamilton, 2007). Three important carbon markets are: the European Climate Exchange, the Chicago Climate Exchange, and the Regional Greenhouse Gas Initiative.

The European Climate Exchange (ECX) is the most widely known market in the world for trading emissions. ECX currently trades two types of carbon credits: EU allowances (EUAs) and Certified Emission Reductions (CERs). The market began in 2005 and was initially focused on trading EUAs. The Exchange began trading futures and options for CERs in 2008. Trading on the ECX has grown since the start of the market. In 2007, the volume of EUAs options traded was approximately 57.5 million tons, in 2008 the volume of EUAs options traded was 243.1 million tons, and thus far the EUAs options traded in 2009 are 154.9 million tons (European Climate Exchange). The ECX is the oldest voluntary carbon market.

The Chicago Climate Exchange (CCX) is currently the only cap and trade exchange for all six GHGs in North America. Membership to the exchange is voluntary; however, this commitment to meet GHG emission reduction targets is legally binding. CCX offers two programs for emissions reductions, allowance and project-based trading. The majority of trading on the CCX comes from allowance-based projects where CCX member companies agree to internally reduce CO_2 emissions (Hamilton, 2007). The

CCX lists the benefits of membership as, "to prove concrete action on climate change and gain recognition for taking early, credible, and binding action" (Chicago Climate Exchange, 2007). The CCX has been criticized for being too industry-friendly in that the required level of emissions reduction was only 1 percent from 2003 to 2006. Moreover, CCX has received criticism for how the company calculates emissions reductions and what activities constitute emissions reduction (Goodell, 2006).

The third voluntary carbon market is the Regional Greenhouse Gas Initiative (RGGI). It is a mandatory carbon market. Ten northeastern states have joined together to cap CO_2 emissions by the power sector, reducing emissions by 10 percent by 2018 (Regional Greenhouse Gas Initiative, 2009). The RGGI was founded in late 2005, and the first compliance period began on January 1, 2009 (Regional Greenhouse Gas Iniative, 2009). The market structure is one where states sell emissions allowances through auctions and use the proceeds to improve energy efficiency and invest in renewable electricity generation technologies (Regional Greenhouse Gas Initiative, 2009).

Carbon Capture and Storage

Carbon Capture and Storage (CCS) is the process of capturing and storing CO_2 that is emitted in the combustion process of electricity generation from fossil fuel sources and processing industries (IPCC , 2005). Carbon Capture and Storage technologies can reduce CO_2 emissions in the atmosphere from electricity generation (Jamasb, Nuttall, & Pollitt, 2006). The technological options for carbon storage include "pre-combustion, postcombustion, and oxy-fuel technologies," and by using these measures, CO_2 can be carried through pipelines and stored underground (Jamasb, Nuttall, & Pollitt, 2006).

CCS technologies are CO_2 abatement strategies to address climate change concerns. Consideration of legal, regulatory, and technical aspects should be taken into account when considering this abatement option (Meyer, 2008). Large-scale investment in equipment and infrastructure is necessary to expand the use of CCS technology. Since investment will be on a large scale, relevant legal and regulatory preparation is required to ensure, "safe, efficient, and environmentally sound" CCS projects (Meyer, 2008).

The EIA (2008) has issued an assessment of CCS technologies. First, there is little possibility that meaningful CCS projects will be installed before 2020. Though the technologies can be commercialized within that time frame, clean coal-generation facilities with around 250 gigawatts (GW) capacity will reduce 90 percent of CO_2, approximately 1 billion metric tons. In other words, CCS will not produce any positive cost benefits compared to other emission reduction technologies. A second issue with CCS is currently that the economic incentives for industries to participate are limited as there is no set policy mandating carbon emission reductions. In summary, further research and development on CCS technologies and systematic approaches to reduce costs are necessary to encourage carbon capture as a feasible CO_2 abatement technology.

<u>Discussion of Cost Curves</u>

The analysis below provides several important comparisons of conventional and renewable generation technologies with and without CCS. The range of policy tools available, such as cap and trade and carbon taxes, have not established a carbon price that is universally adopted. Therefore, for this analysis, carbon price is listed in a range of 0-100 US$ per metric ton of CO_2 . It is important to note the following model assumptions: all generation technologies are set to have a 40-year operating life, capacity is set to 500MW, all dollar values are reported in US$ 2007, and carbon capture and storage is currently set to represent a site that is 50km from an injection site that injects into a saline aquifer (Please see Appendices for complete methodology of model assumptions).

<u>Cost of Electricity from Conventional Generation Technologies</u>
The mix of conventional electricity generation technologies has been explored in the Supply section of this report. To reiterate, conventional fuels included in this discussion are: pulverized coal (PC), natural gas combined cycle (NGCC), nuclear, and hydroelectric.

Once a carbon price is established and the cost to emit CO_2 becomes more expensive, electricity generated from fossil fuels becomes more costly. Figure 16 demonstrates how the cost of generating electricity from PC and NGCC increases with a rise in the carbon price (US$ per metric ton of CO_2). In this scenario, the cost of electricity generation from nuclear and hydroelectric remains constant, making them economically attractive; however, there are geographic and political implications to these generation technologies that may decrease their economic advantages (See Supply for discussion of geographic and political limitations).
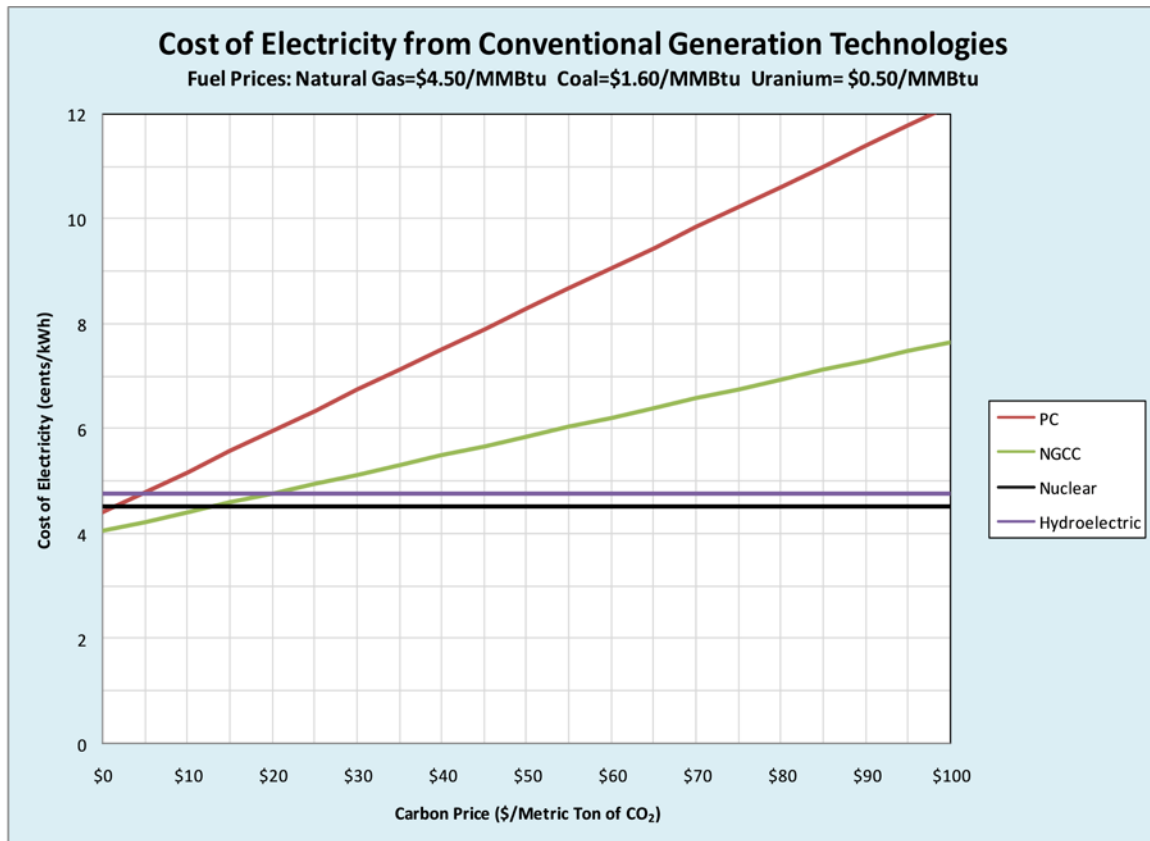

Figure 16: Cost of Electricity from Conventional Generation[7]

Cost of Electricity from Fossil Fuel Generation Technologies
The primary abatement technology to reduce emissions from fossil fuel-based electricity generators is CCS. The capital requirements for CCS include components that capture CO_2 and compress the gas for transport, pipelines and injection infrastructure.

Figure 17 depicts standard fossil fuel generation technologies. The dotted lines represent the cost of electricity generated at plants with CCS technology. These are compared to generation facilities without CCS. The graph demonstrates that NGCC is the least-cost method for electricity generation up to a carbon price of US$63 dollars per metric ton of CO_2. Beyond this carbon price, the least-cost generation technology is NGCC with CCS. Even though natural gas represents the least-cost method of electricity generation, it is important to note that natural gas prices are volatile, whereas coal remains stable.

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[7] Figure generated with information from this report.
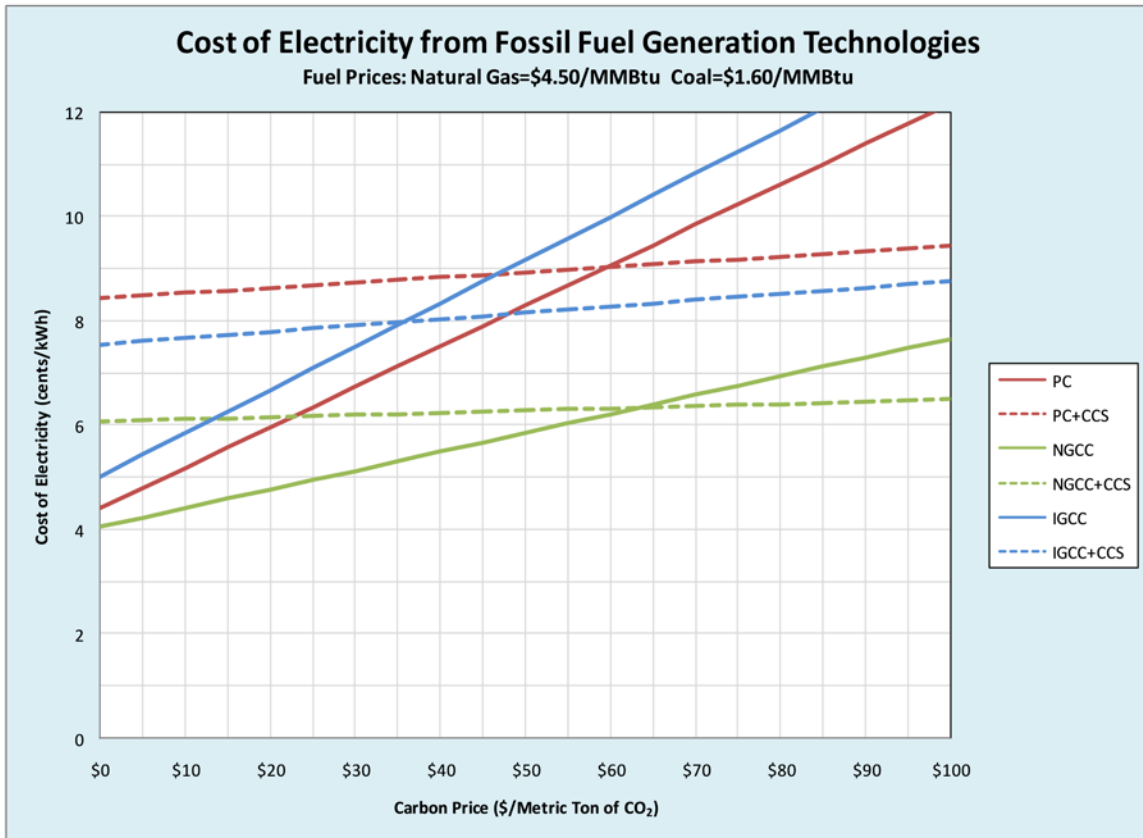
Figure 17: Cost of Electricity from Fossil Fuel Generation Technologies[8]

Cost of Electricity from Fossil Fuel Generation Technologies: Increased Natural Gas Prices
Figure 18 assumes a natural gas price of US$8 per MMBtu; an increase of US$3.50 per MMBtu from
Figure 17. PC becomes the least-cost generation technology up to the carbon price of approximately
US$48 per metric ton of CO_2. Beyond this carbon price, IGCC with CCS becomes the least-cost
generation technology. Electricity generation from PC with CCS will never cost less than IGCC with CCS
given a reasonable carbon price per metric ton of CO_2. Therefore, it is not likely that new PC with CCS
facilities will be implemented in high carbon price scenarios.

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[8] Figure generated with information from this report.

Cost of Electricity from Fossil Fuel Generation Technologies
Fuel Prices: Natural Gas=$8.00/MMBtu Coal=$1.60/MMBtu

Figure 18: Cost of Electricity with Higher Natural Gas Prices[9]

<u>Comparison of Renewable and Non-Renewable Generation</u>
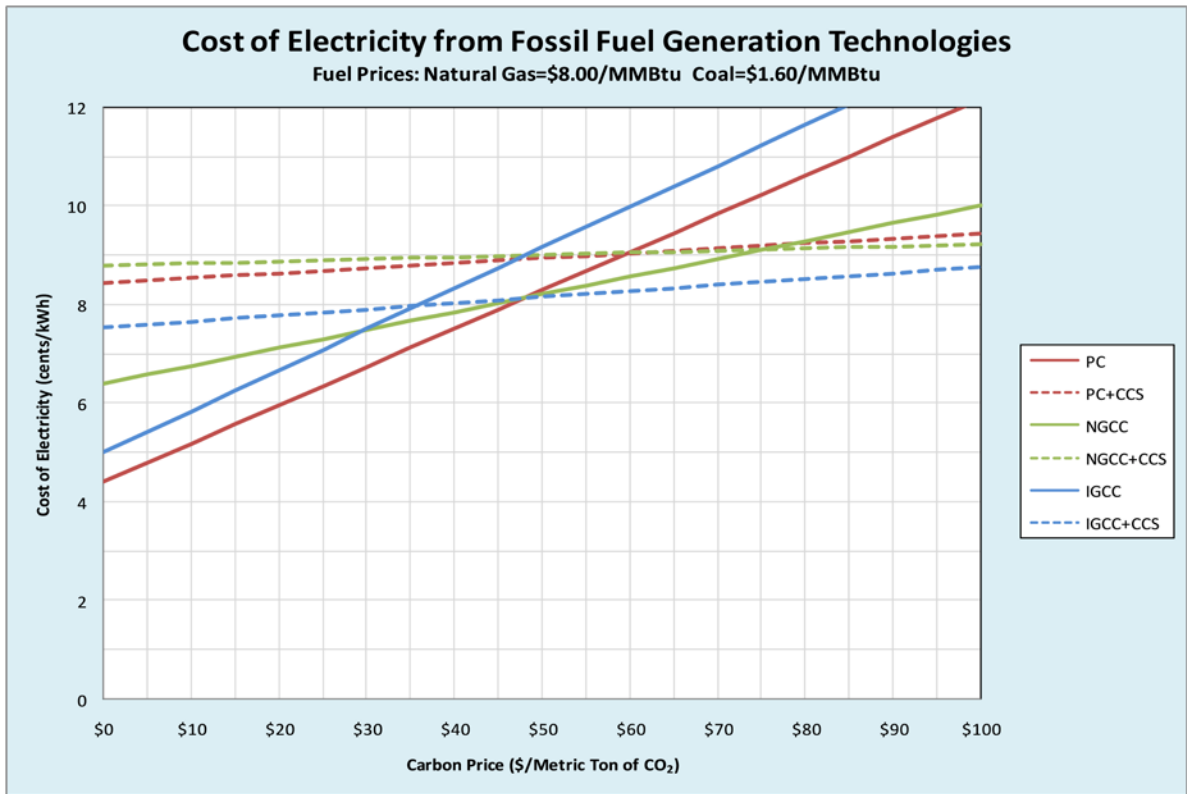Figure 19 includes non-fossil fuel-based generation technologies, such as wind, solar, geothermal, hydroelectric, and nuclear, in addition to non-renewable generation sources. As depicted below, nuclear and hydroelectric provide the least-cost method of electricity generation at higher carbon prices. These generation technologies remain the least-cost method of electricity generation even when compared to carbon-intensive electricity generation methods with the addition of CCS technology. As was stated in the previous analysis, PC with CCS never generates electricity at a lower cost than IGCC with CCS; therefore, this technology is not further analyzed. In addition, it should be noted that concentrated solar is the most expensive electricity generation source at any carbon price. An important intersection on the graph to note is at US$13 per metric ton of CO_2, nuclear becomes the least-cost generation method for electricity. A second noteworthy intersection is at carbon prices greater the US$48 per metric ton of carbon, wind is less costly then IGCC with CCS.

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[9] Figure generated with information from this report.
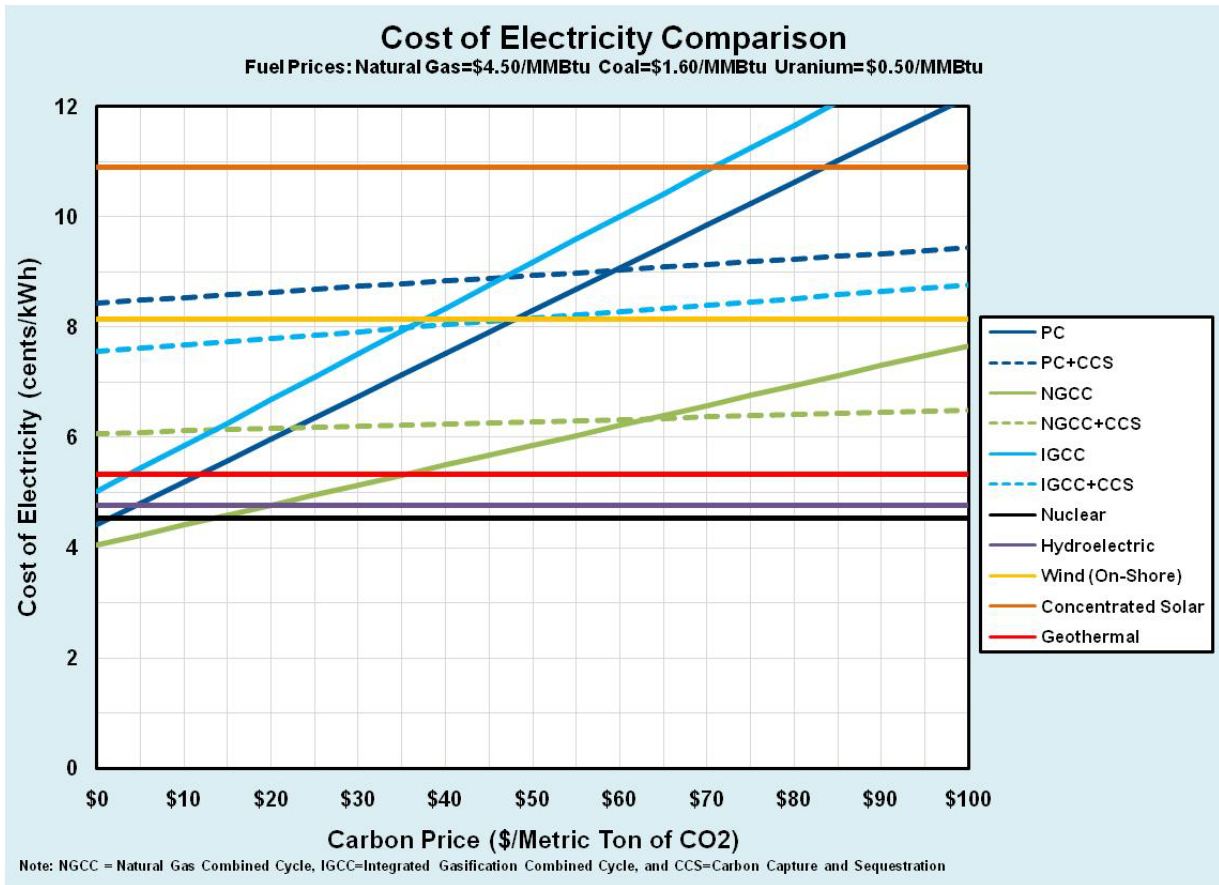
Figure 19: Comparison of Various Renewable and Non-Renewable Electricity Sources

Comparison of Renewable and Non-Renewable Generation: Senstivity Analysis of Coal Prices

Historically, coal prices have remained relatively stable, especially when compared to natural gas prices. Figures 20 and 21 show what happens with an increase in coal price per MMBtu at the natural gas price originally used as a baseline price, US$4.50 per MMBtu, and at the increased natural gas price of US$8.00 per MMBtu. The non-renewable generation technologies are also analyzed with CCS. Also compared in the graphs are renewable generation technologies.
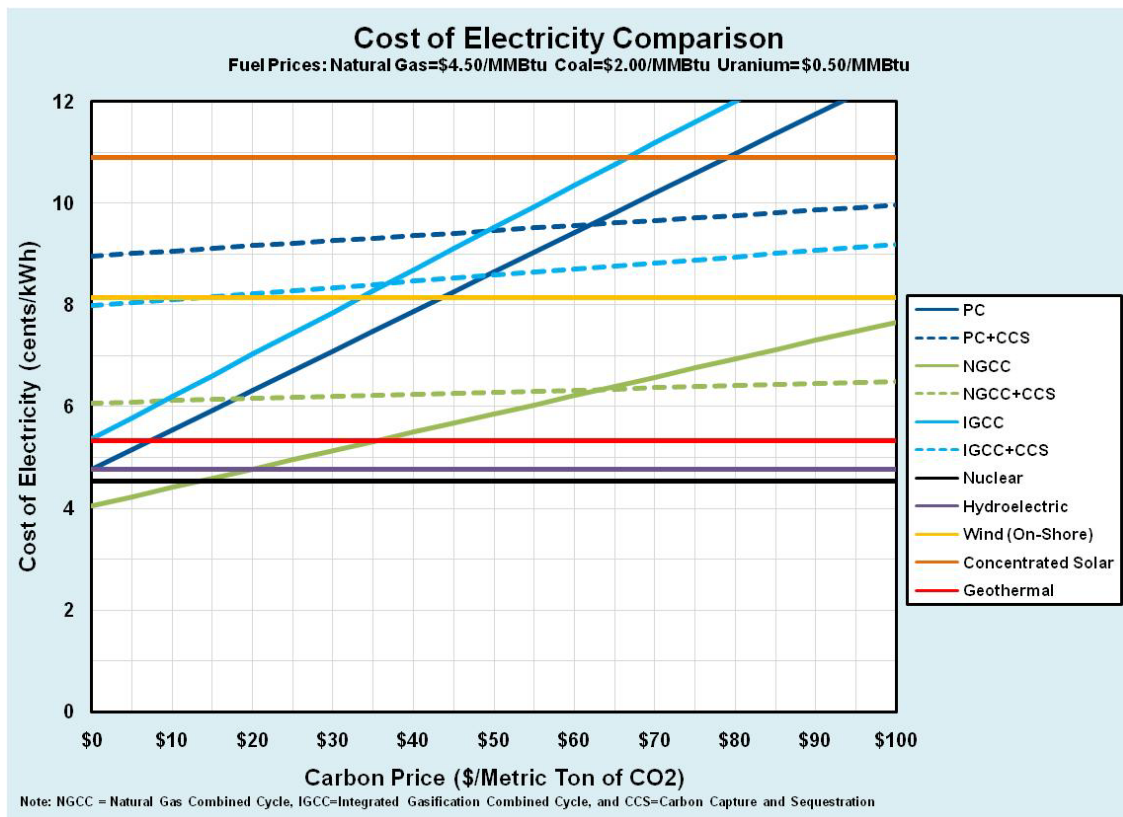
Figure 20: Cost of Electricity Comparison (Natural Gas = $4.50/MMBtu)

As is expected with an increase in coal price, the cost of electricity generation from PC and IGCC plants is higher. With natural gas prices at US$4.50 per MMBtu and coal priced at US$2.00 per MMBtu, nuclear and hydroelectric continue to remain the least-cost generation technology. Geothermal is also a low-cost generation technology in this example. Previous discussion has explained the geographic limitations of hydroelectric and geothermal electricity generation. Nuclear electricity generation faces the challenge of mixed public perception and political constraints. However, if not located in an area suitable for geothermal or hydro, and considering the constraints of nuclear, natural gas combined cycle appears to be the most acceptable, locationally independent, and least-cost technology available to generate electricity.

The sensitivity analysis also compared coal priced at US$2.00 per MMBtu when natural gas was increased to US$8.00 per MMBtu. This analysis is presented in Figure 22.
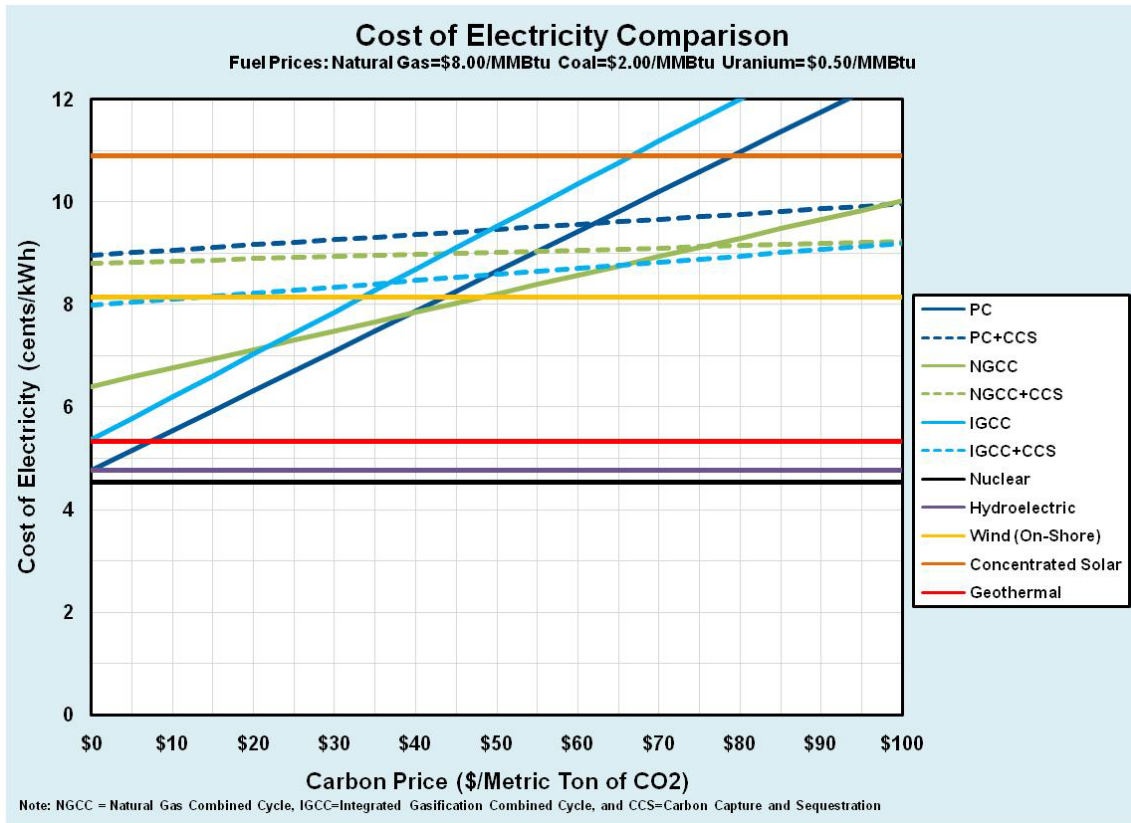
Figure 21: Cost of Electricity Comparison (Natural Gas = $8.00/MMBtu)

In this scenario, renewable generation technologies, like wind become more attractive from a cost perspective. For example, at around US$48 per metric ton of CO_2 wind becomes a least-cost generation technology compared to NGCC. However, given the lack of storage technologies for wind and the intermittent nature of wind supply, this technology is not a dependable source of energy when it is needed. If constraints limit the use of geothermal, nuclear, hydroelectric, and wind generation technologies, the next least-cost generation method is PC up to a carbon price of US$39 per metric ton of CO_2, after which NGCC become the least-cost generation technology.

Chapter III: Electricity Tomorrow

This study uses two projections to highlight the possible future of electricity. These projections are based on the assumption that increased investment into renewable generation technologies will drive down the capital cost of these technologies. To reflect this, a 25 percent reduction in the capital cost of renewable and nuclear sources is incorporated into the model.[10] For a complete list of the model's assumptions, see Appendix C.

The first projection (Figure 22) assumes a price of US$ 4.50 per MMBtu. At a carbon price around US$13 per metric ton of CO_2, geothermal becomes least-cost compared to NGCC. At a carbon price of US$63, on-shore wind becomes the least-cost technology over NGCC electricity generation technology.
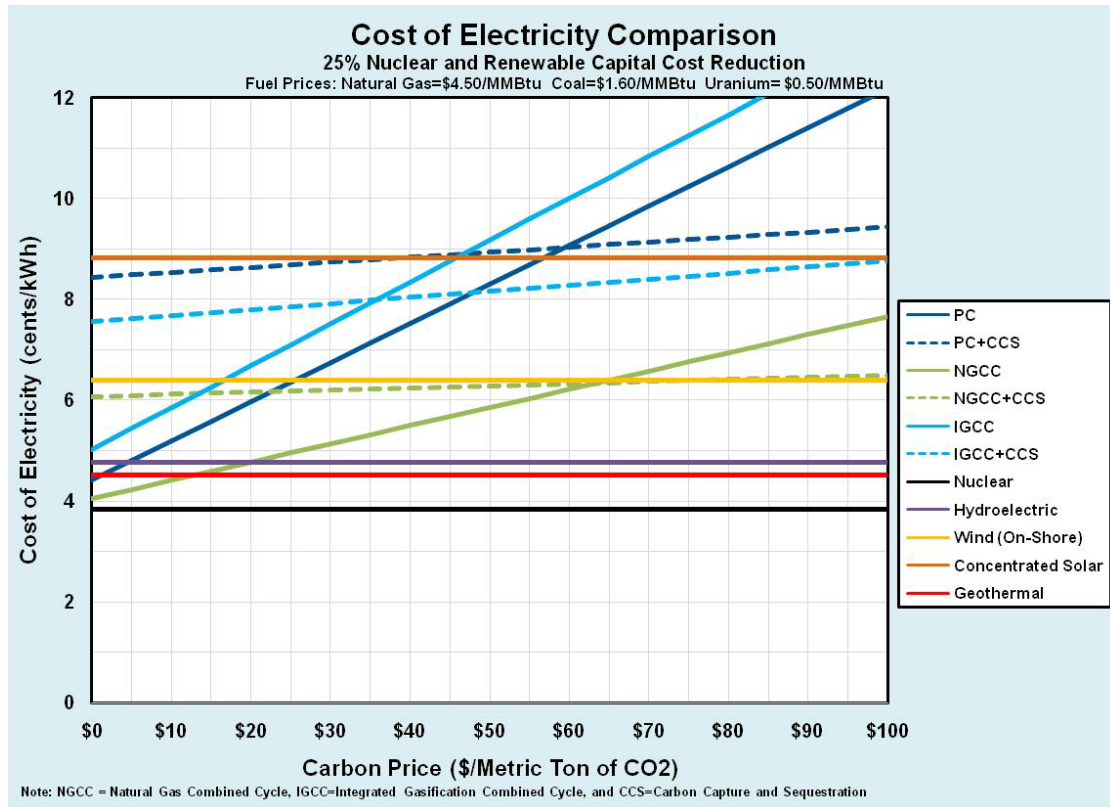
Figure 5 Cost of Electricity Comparison (Natural Gas=$ US$ 4.50 per MMBtu)

The next projection maintains the 25 percent capital cost reduction for nuclear and renewable technologies but also reflects the price volatility of natural gas by increasing the fuel price to US$ 8.00 per MMBtu. As a response to this price increase, renewable technologies become more cost-competitive. On-shore wind becomes a less expensive generation technology compared to NGCC at all carbon prices, and no fossil fuel is least-cost beyond a carbon price of US $25 per metric ton of CO_2.

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[10] Although a renewable electricity generation technology, hydroelectric does not reflect this capital cost reduction as it is not an emerging technology.
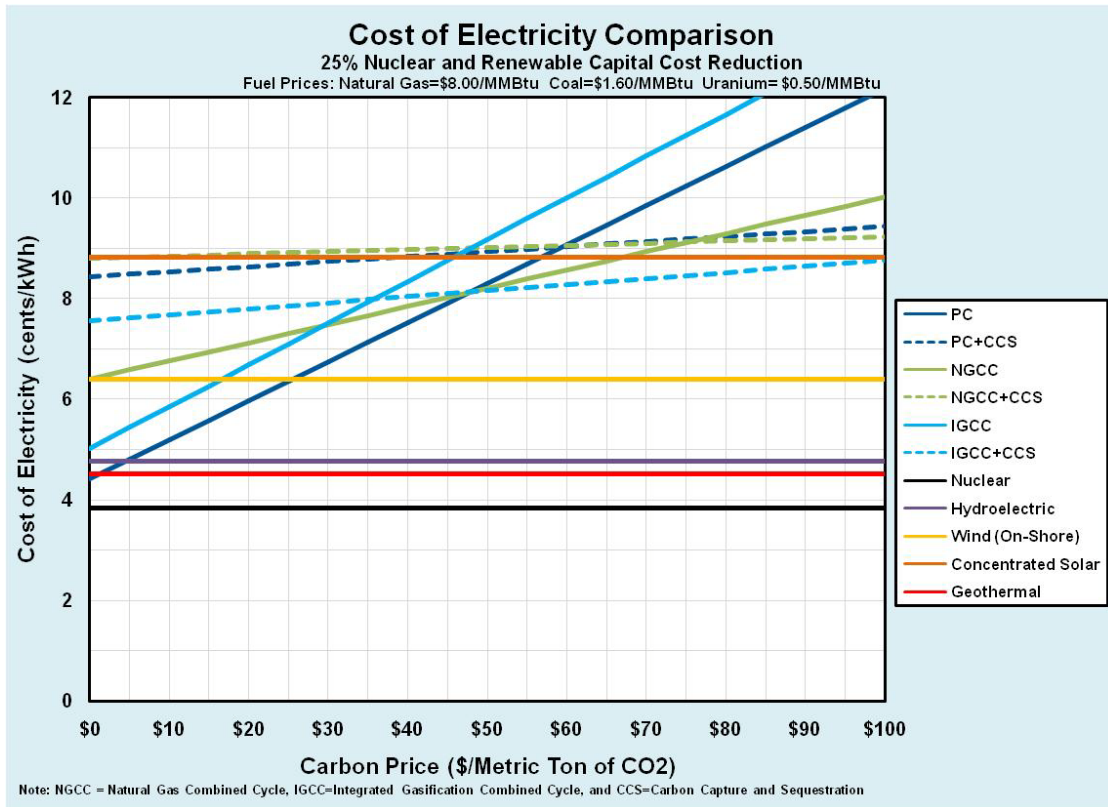
Figure 23: Cost of Electricity Comparison (Natural Gas=$ US$ 8.00 per MMBtu)

FURTHER PROJECTIONS

Grid Implications

The growth of large-scale renewable generation technologies will be dependent upon the implementation of HVDC transmission and CAES. Production fluctuations are a concern with increased use of renewable generation technologies. The current grid is susceptible to damage from these production fluctuations. HVDC can support distribution of electricity generated by renewable sources because it allows intermittent electricity from renewable sources to travel further without incurring line losses. This is important because renewable are geographically dependent and typically located far from population centers where electricity is needed (Kirby, 2002). HVDC can change power flow quickly, which is important for grid reliability. Control of the power flow is what creates stability in the system, not only for the HVDC connections (Woodford, 1998).

Supply Implications

According to the EIA, the overall supply of electricity will double by 2030. From 2005 to 2030, total net electricity generation will grow at an average annual rate of 2.6 percent. At this rate, worldwide electricity generation will increase from 17.3 trillion kWh in 2005 to 24.4 trillion kWh in 2015. By 2030, electricity generation will reach 33.3 trillion kWh. Growth rates in electricity generation, however, differ between OECD and non-OECD countries. Whereas non-OECD electricity generation is expected to grow by an average of 4.0 percent per year to the year 2030, OECD generation will grow by an average annual rate of 1.3 percent (Energy Information Association, 2008). These figures do not take into account geographic restrictions of electricity generation or the baseline conditions of OECD and Non-OECD countries.

The following analysis extends the EIA projections 30 years up to 2060 (see Appendix D for the methodology). Projections for each fuel source to 2060 are based on each source's average annual rate of growth. Extension of the EIA projections from 2030 to 2060 shows a 350 percent increase in the overall electricity generation. Generation trends are different for OECD and non-OECD countries. In OECD countries, natural gas is predicted to account for 30.7 percent of electricity generation in 2060, displacing generation from petroleum. Coal will account for 36.1 percent of electricity generation and will include carbon capture if the price of carbon is greater than US$47 per metric ton of CO_2. This estimate represents a decline from the current percentage of 38. The share of electricity from nuclear power in OECD nations will decline to 19.6 percent of electricity generation in 2060. According to the EIA, this decline will be largely the result of actions in OECD Europe, "where several countries (including Germany and Belgium) have either plans or mandates to phase out nuclear power, and where some older reactors are expected to be retired and not replaced"(Energy Information Association, 2008). Waste disposal and reprocessing concerns slow the growth of nuclear and partly explain this decline. Nuclear power is also a water-intensive generation technology. At the same time, electricity from nuclear generation is the least-cost technology according the projections made in this study. For this reason, nuclear electricity generation is projected to grow in OECD countries. The projections also show that non-hydro renewable electricity will grow as a generation source, from nearly 4 percent to 4.5 percent, but remain limited by geographic considerations. Hydroelectric power, however, declines to 8.6 percent in 2060 from nearly 14 percent today.

Electricity generation in non-OECD countries will utilize different shares of both renewable and nonrenewable resources compared to OECD countries. In 2060, natural gas will increase to 28 percent of electricity generation. Growth in fossil fuel-based electricity generation capacity will drive an almost 20 percent increase in the use of coal to 62 percent of total non-OECD electricity generation. This reflects the resource availability. China's rapidly expanding coal-based generation capacity will be a major factor contributing to this increase. The share of electricity generation from nuclear grows to 7 percent by 2060, from its current level of 5 percent. Therefore, nuclear power will only represent a small portion of non-OECD electricity generation. Hydroelectric power substantially declines, dropping from 22 percent today to 4.7 percent in 2060. Non-hydro renewable sources will also decline but are not major sources of electricity generation in the future. Regardless of the shifts in the mix of electricity generation technologies, coal remains the primary fuel source for electricity generation in 2060. (See Appendix D for a detailed summary of the future electricity generation mix)

According to this study's analysis, carbon prices will not reach levels that will substantially alter fuel source mix. Even in a best-case scenario, renewable electricity generation requires high carbon prices to be cost-competitive with non-renewable sources. The analysis also finds that there will be a rapid expansion of fossil fuel generation in non-OECD countries. The reason for this is that fossil fuels remain the cheapest sources to satisfy the rapidly growing demand for electricity. The continued use of fossil fuels and the environmental impacts of this use may lead to policies that regulate CO_2 and other GHG emissions.

Conclusion

Based on this research, world population growth and increasing global reliance on electricity as a source of usable energy in the future are expected to dramatically expand the total amount of electricity generated and delivered. Electricity generation and consumption increase 350 percent by 2060. The relative fuel source mix will remain largely unchanged. Climate change concerns stand to influence electricity technologies used in the future. Generation technologies will change due to the continued reliance on coal and improvements in CCS. Given population and economic growth occurring primarily in non-OECD countries, effective GHG mitigation strategies must include the developing world.

Chapter IV: Four Case Studies

During Latin America's third wave of democratization in the late 20th century, Brazilian state-run electricity utilities transitioned to a partial private enterprise model, which heavily influences electricity in Brazil today. A reliance on hydroelectric dams to provide the majority of electricity and transmission over long distances is unique aspect of Brazil's utility structure. Demand growth and a concentrated industrial sector are important considerations in projecting future electricity needs.

THE ENERGY MARKET

Brazil had 90.7 gigawatts (GW) of installed generating capacity in 2005, with the single largest share (85 percent) being provided by hydropower. In 2005, the country generated 396.4 billion kWhs (BkWh) of electric power, while consuming 368.5 BkWh. Smaller amounts come from conventional thermal, nuclear, and other renewable sources (EIA, 2008a). Brazil generates roughly 12 percent of the world total hydroelectric power (EIA, 2008a). This dependence on renewable sources for generating its electricity, both recently and in the future, is illustrated by Figures 24 and 25.

Net Electricity Generation by Fuel Source in 2005 (Trillion Kilowatt Hours)
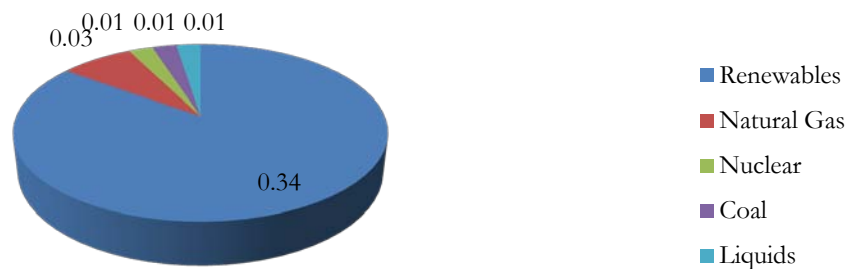

Figure 24: Brazil's Net Electricity Generation by Fuel Source in 2005 (Trillion KWhs) (EIA, 2008b)

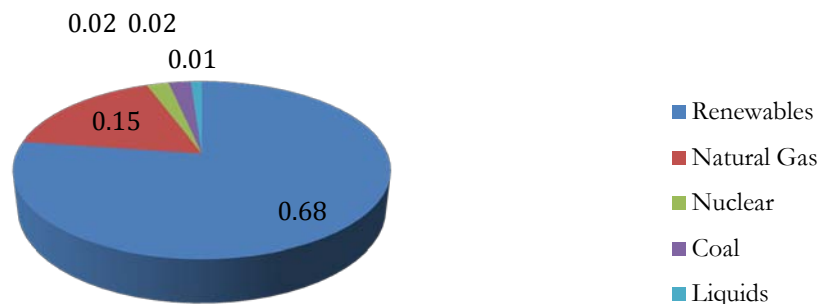**Predicted Net Electricity Generation by Fuel Source in 2030 (Trillion Kilowatt Hours)**

Figure 25 Brazil's Net Electricity Generation by Fuel Source in 2030 (Trillion KWhs) (EIA, 2008b)

Breakdown of Renewable Electricity Generation by Type in 2005 (Billion Kilowatt Hours)
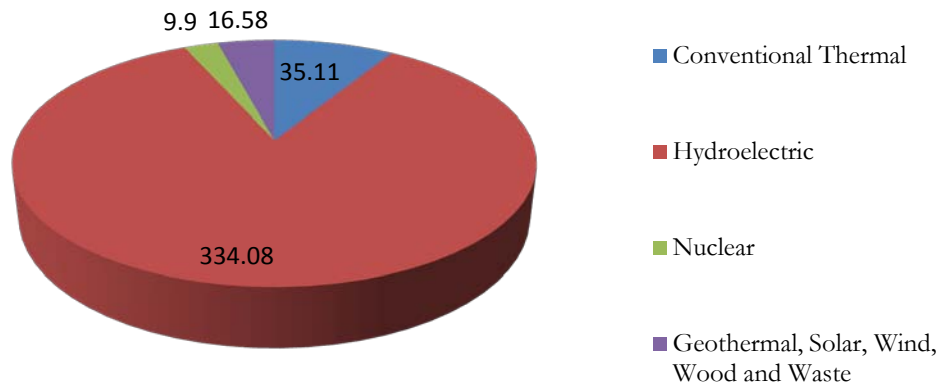

Figure 26: Brazil Renewable Electricity Generation by Type (Billion Kilowatthours)[11]

Brazil's rising GDP and increasing demand for electricity are factors shaping its current and future electricity sector. One study notes that since 2004 GDP has increased at an average 4.3 percent per year, while electricity demand has risen by an average of five percent per year (EIA reference: Global Insight Inc.). Economic growth has spurred a strong demand for electricity in the region and has tested infrastructural limits (EIA, 2008a). In 2000, the National Energy Policy Council set a strategic target for the reconfiguration of the Brazilian energy matrix so that natural gas will be responsible for 12 percent of the matrix by 2010 (Fernandes, Alonso, & A. Fonseca, 2005).

Market Structure

The development of the Brazilian electricity industry resulted in a complex industrial structure. There are only three relevant distribution areas run by state companies, Minas Gerais (CEMIG), Santa Catarina (Centrais Eletrica) and Paraná (COPEL). The federal government is the controlling shareholder of Eletrobrás, which controls 50percent of the capital belonging to Itaipu Binacional dam belonging to Brazil (Ministry of Mines and Energy). Today 59 companies operate in the generation sector and 64 utilities in the distribution segment (E.L. Fagundes de Almeida, 2005). The long-term auction market structure provides contracts that insulate investors against economic or environmental risk (Karmacharya, 2008).

Tariffs

Power costs in Brazil are low. This reflects the historical reliance on cheap hydropower that was built by the state and is largely amortized. Nevertheless, tariffs are relatively high as result of system charges and taxation, especially for residential consumers (Adilson de Oliveira, 2005). Electricity prices for households in Brazil averaged US $0.19 per kWh, compared to US $0.10 in the US in 2006 (EIA, 2008a).

ELECTRICITY POLICY

Beginning in the 1930s, and ending only in recent decades, Brazil pursued a statist development policy. Driven by the conditions of the Great Depression, the Brazilian government became increasingly involved in the production of basic inputs, including electricity (The James A. Baker III Institute for Public Policy of Rice University, 2004). Notably, the Water Act of 1934 granted property rights in hydropower to the federal government, and confusion over the law's scope left many private companies

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[11] 2005 Basic Table 6.3 (http://eia.doe.gov/iea/elec.html)

unwilling to invest in the industry (Karmacharya, 2008). It was during this period that the large state-owned enterprises that still dominate the sector, such as Eletrobrás, came into existence.

Faced with the deterioration of the statist model in the late 1980s, Brazil embarked on the reform of its electricity policy, and energy policy more generally. In 1996, President Cardoso instituted the Project for Restructuring the Brazilian Electric Sector (RESEB) with the aim of creating a more competitive electricity market to draw in more private investment. As part of the reform process, Brazil also created ANEEL (National Agency of Electricity), linked to the Ministry of Mines and Energy, which now serves as the principal regulatory body for the electricity sector (The Agency, 2008). For diesel generators in rural areas, the Brazilian government pays subsidies through a tax charged to all electricity consumers, called the Fuel Consumption Account (da Cunha, Walter, & Rei, 2007). Also, in 2002 the low-income social tariff was created to benefit low-income families through energy tariff discounts. The total subsidy amount in 2006 was US$650 million (USAID, 2007).

Transition to a new model

Brazilian institutional development is marked by the economic expansion and structural transition of electric utilities. Sector reform includes injecting market-based competition, privatization, and attempts to increase foreign investment aimed at debt reduction. According to Bajay (2006), insufficient private investment in new power stations caused a serious power shortage in 2001. The new institutional model was characterized by reducing public debt via privatization of state-owned utilities that dominated the pre-reform sector (Bajay, 2006). The Pre-Reform model included a vertically bundled industry consisting of a few state owned companies. Foreign investors were banned, and generation, transmission and distribution were governed by regional/state monopolies. Post-Reform, the industry was vertically unbundled and privatized. Restrictions on foreign investors were lifted, competitive generation and distribution began, and regulated monopolies on transmission systems were formed (E.L. Fagundes de Almeida, 2005).

Regulatory structure

In 1998, Brazil passed Law 9648/98, which further liberalized the electricity sector. Most notable of its features were provisions for the Wholesale Electricity Market (MAE), and the National Electricity System Operator (ONS) (Peres). The purpose of the MAE was to "intermediate all electricity sale and purchase transactions in each of the interconnected electricity systems," shifting electricity sales from short-term purchases to long-term bilateral contracts to overcome volatility in the spot market (Peres). The ONS has four functions:

"*a)* to guarantee free access to the transmission network in a non-discriminatory fashion; *b)* to promote the optimal operation of the electrical system, planning and programming the operation of centralized dispatch of generating output; *c)* to provide incentives for the expansion of the system at the lowest possible cost; and *d)* to manage the basic transmission networks" (Peres).

In 2001, Brazil was faced with an energy crisis brought on by its heavy reliance on hydropower, unusually low rainfall, and insufficient development in electricity production and transmission. In response, the government created the Crisis Management Board (CGE), a body headed by the president, which imposed a quota system, forcing residential and industrial users to reduce consumption by 20 percent or face either cutoffs or tariffs (The James A. Baker III Institute for Public Policy of Rice University, 2004). President Cardoso also announced his intention to finance the construction of 55 new gas-fired power plants to diversify Brazil's electricity supply. However, only 19 plants were finished. (The James A. Baker III Institute for Public Policy of Rice University, 2004). As a result, Brazil remains vulnerable to another drought.

In 2003, newly inaugurated president Luiz Inácio Lula da Silva initiated another round of regulatory reforms through Law 10,848/04. First, energy supply and demand is now coordinated through a 'pool' and operated by the Empresa de Planejamento Energético (EPE). This pool sets electricity prices based on three to five year projections by suppliers and effectively prohibits self-dealing by vertically integrated

firms. Second, the law created a parallel 'free' market called the Ambiente de Contratação Livre (ACL), which is not bound by the price set by the EPE. Large consumers (10 mW +) are required to give several years notice to their supplier before switching between markets. Third, the government reinforced the role of its regulatory bodies in long-term planning to promote strategic technological development trend monitoring in power supply and demand (Organization for Economic Co-Operation and Development, 2004).

SOCIAL CONTEXT

Brazil is a country where roughly 97 percent of its population has access to electricity (Organization for Economic Co-Operation and Development, 2004; United Nations Development Programme), although 6.5 million are estimated to be without access (United Nations Development Programme). As would be expected of a country still developing, regions of Brazil exhibit wide disparities in their access to and use of electricity. The southeast region, containing the cities of Sao Paulo and Rio de Janeiro, uses the largest share of Brazil's electricity (58 percent), whereas the north with 8 percent of the population, consumes only 5 percent of its electricity (Ghisi, Gosch, & Lamberts, 2007). Besides disparities between geographic regions in electricity access, there can be wide gaps between rural (73 percent with access) and urban (98.8 percent with access) regions (Energy Sector Management Assistance Program, 2005).

A lack of access to electricity has been noted as a potential constraint on a country's development and growth, particularly impacting the poor. The northern and northeast regions of Brazil have been described as the poorest regions, with "approximately 2.6 million inhabitants of rural areas in the North of Brazil" without electricity access. This disparity in access between the north and other regions of Brazil is biased by the difficulties in establishing connections in remote regions or by environmental or legal concerns (da Cunha, Walter, & Rei, 2007). In an effort to promote the "social and economic development of rural and isolated communities," (da Cunha, Walter, & Rei, 2007) the national government has "established the goal of *universal access* to electricity services" by 2010 (Energy Sector Management Assistance Program, 2005). Currently, electricity in remote areas of the Amazon is often generated from using diesel generators, with the operating costs subsidized by the government (da Cunha, Walter, & Rei, 2007).

Brazil's demand for electricity is expected to continue growing, especially as there are still areas without access, and as people's incomes increase, consumption would be expected to rise (Ghisi, Gosch, & Lamberts, 2007). In order to meet the projected future demand for electricity, there is a need for continued development of new generation sources (Organization for Economic Co-Operation and Development, 2004). The construction of hydroelectric dams is seen by the government, industry, and other stakeholders as one method to meet Brazil's current and future need for electricity (Fearnside, 2005; Fearnside, 2006). A hydroelectric dam can be a controversial topic due to the potentially negative environmental and social impacts arising from its construction. Issues of social justice can become a concern because of the need to resettle communities, negative impacts on indigenous people's way of life, and the loss of established infrastructure (Fearnside, 2006). Another social issue of concern raised by Fearnside (2006) is whether the electricity produced by a dam will benefit the public or primarily companies involved in energy intensive production processes, whose final product is exported (e.g. aluminum).

Organized resistance to dam construction in Brazil has a history starting in the late 1970s (McCormick, 2007). Even though the approval process for a new dam requires an environmental impact statement and a public hearing (Fearnside, 2005), controversy often arises due to perceptions of a lack of public input in the process, insufficient consideration of the environmental and social costs of a dam, and environmental impact assessments that were biased in favor of a dam's construction (McCormick, 2007). This resistance and Brazil's recent history of encouraging public participation in government decision-making, has resulted in the formation in certain regions of a variety of collaborative efforts between those affected by a proposed dam and outside experts. These efforts have created forums where local knowledge and outside technical expertise is more easily exchanged, often resulting in a more complete understanding of a project's overall benefits and costs. This increased knowledge of government plans and policy, as well

as the affects of an individual project, has enabled those opposed to a dam's construction to more effectively advocate for its modification or cancellation (McCormick, 2007).

ENVIRONMENT

Hydroelectric Dams

Brazil is an example of a country that meets its electricity needs predominantly through the use of hydropower, with the construction of additional hydroelectric dams seen as a way to meet Brazil's current and future demand for electricity (WCD, n.d.). Although considered less damaging to the environment, there are still environmental consequences to its use. One of the main consequences is the release of greenhouse gases (e.g. CO_2) due to the conversion of land where the power generating facility is built. As the major sources of CO_2 emissions in Brazil are due to changes in land use (Persson & Azar, 2004; Quadrelli and Sierra Peterson, 2007), the building of additional hydroelectric dams could exacerbate the issue.

The construction of hydroelectric dams can also impact the environment by negatively impacting areas under legal protection. This is demonstrated by the Brazilian Amazon region, which while considered an excellent location for hydroelectric dams, the majority of the area is under some form of legal protection, such as for a protected area or indigenous reserve (da Cunha, Walter, & Rei, 2007). Of the total area of the Amazon Region, 41 percent is reserved for Conservation and Indigenous Lands. Expansion of dams into these areas requires the enlargement of those areas into Amazon River basin (Pereira, Soaresa, Oliveiraa, & Queiroza, 2007). This is demonstrated by the fact that in the past there were plans for the construction of 79 dams in the region, potentially resulting in the flooding of 3 percent of the total forested area (Fearnside, 2005). Other potential environmental consequences are damages to the habitat, such as negative impacts on water quality (i.e. increased sedimentation), loss of habitat, and reduction of migration corridors (WCD, 2000). The clearing of large areas of forested land in order to establish the needed transmission lines to carry the electricity from the dams in Amazon region to other areas of Brazil, such as the more industrialized southeast region is another major environmental concern.

Diesel Generators

Another environmental concern is increasing use of diesel generators. In 2003 the federal government launched the Luz para Todos program (Light for Everyone) to expand electricity access to an additional 12 million people until 2009. In order to achieve the planned expansion goals in rural and isolated areas, most of these companies turn to diesel generators, mainly because of the low capital cost (da Cunha, Walter, & Rei, 2007). In isolated communities however, electricity provision through the use of small diesel generators can be unstable, expensive and environmentally inappropriate (i.e. releases pollutants and greenhouse gases) (da Cunha, Walter, & Rei, 2007).

CONCLUSION

Brazil's long-term goal of diversifying its electricity generation sources has been difficult but necessary. Producing enough electricity to meet rising demand will require less dependence on hydropower and an increased reliance on natural gas. This is necessary to lessen the uncertainty and vulnerability of the current supply model to future droughts and economic conditions (Fernandes, Alonso, & A. Fonseca, 2005). The heavy reliance on hydropower for electricity and the relatively recent privatization of electric utilities are what make Brazil unique. Meeting the challenges related to an increased need for fuel source diversification and mitigating the social and environmental concerns arising from strong industrial and residential demand will shape Brazil's electricity future.

The future of China's electricity industry lies in the country's ability to develop a sustainable energy policy, while maintaining high economic growth rates. Though China continues to initiate sound energy policies, the overreliance of inexpensive coal coupled with the growing demand for electricity, is forcing China to make difficult decisions to balance social and economic development and environmental concerns. Furthermore, weak policy reform causing ineffective enforcement of industry regulations has led to limiting the development of a desired open-market-economy.

THE ENERGY MARKET

Coal

China is both the world's biggest producer and consumer of coal, representing more than a third of global coal production and consumption (Beauregard-Tellier, 2007). China had a coal output of 2.23 billion tons in 2005 - nearly double the amount produced in the US (Coal and Climate Change Facts, 2009). China derives 80 percent of its electricity generation is from coal (Watts, 2005). In 2004 coal output increased by 16.2 percent, and electricity generation increased in the same period by 15.8 percent (BBC, 2004).

Even when investing in pollution control mechanisms, coal can still be maintained as economically competitive (Coal and Climate Change Facts, 2009). The Chinese government has regulated the price of coal to promote development by reducing the impacts of rising energy prices on social equity and political stability. As a result, power generators have adjusted their behavior to adapt to the pricing by operating at below full capacity (Forbes, 2008). The average efficiency in power plants in China is less than in industrialized countries because the average size of the power plants is small (Michaelowa, Jusen, Krause, Grimm, & Koch, 2000). Average efficiency of coal-fired generation in 2005 was 32 percent, and it is expected to climb to 39 percent by 2030 (International Energy Agency, 2007). However, for improved efficiency to occur in the near future, proper economic incentives should be given to utility companies (McKinsey&Company, 2009).

The average annual per capita electricity consumption in China is low, at 1,700 kWh. This is approximately five times less than individual consumption rates in industrialized nations such as the US and Canada. However, as China's economy continues to grow, electricity consumption per capita will increase. In response, China is building, on average, two new coal-fired power plants every week. By 2030, it is estimated that China will have contributed more than half of the increase in the world's coal-fired electricity generation (Beauregard-Tellier, 2007). Figure 27 shows the projected electricity production in China from 1990 to 2030 comparing coal to other energy sources. Coal use accounts for 20 percent of global greenhouse gas emissions (Coal and Climate Change Facts, 2009). China's per capita emissions constitute approximately 50 percent of the global CO_2 (Michaelowa, Jusen, Krause, Grimm, & Koch, 2000), and the growing energy demand will most likely lead to increases in coal consumption (Coal and Climate Change Facts, 2009).

China is the second largest greenhouse gas emitter in the world behind the US, and its emissions have increased by about 80 percent since 1990 due to the increased amount of coal generated electricity (Pew Center on Global Climate Change, 2007). It is projected that China's average annual growth in energy-related CO_2 emissions will surpass the US by about 15 percent in 2010 and by 75 percent in 2030 (Energy Information Administration, 2008).
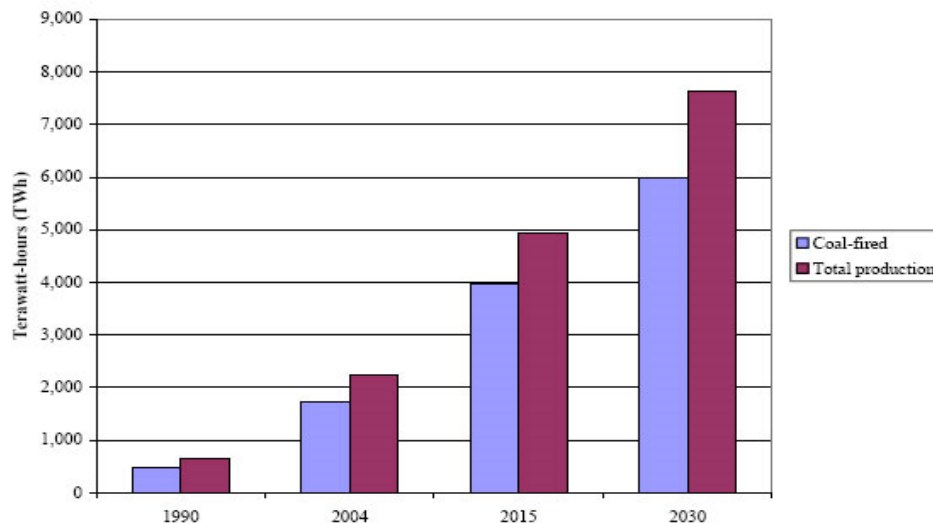
Figure 27. Electricity Production in China, 1990-2030(Beauregard-Tellier, 2007)

Alternate Sources

Although the majority of China's electricity is coal-generated, the growing electricity demand and concerns regarding CO_2 emissions is forcing China to consider diversifying electricity sources. Currently, China is the largest producer of hydroelectricity in the world. However, hydro is not increasing at the same rate as other resources. Thus, its share of total electricity generation is presumed to decrease from 16 percent in 2005 to 12 percent in 2030 (International Energy Agency, 2007). While hydropower produces little CO_2 emissions, alternate environmental concerns exist. The degradation of wildlife directly related to altering freshwater ecosystems is one such concern. The construction of dams often displaces millions of people, leading to controversial social concerns (World Wide Fund for Nature; World Resources Institute, 2004). Despite these concerns, large-scale, small-scale, and pumped storage projects are expected to grow in the future (State Council of the People's Republic of China, 2007).

Though hydropower accounts for the majority of China's renewable resources, China is expected to implement additional clean technologies, potentially accounting for three percent of the total electricity generation by 2030. Wind power capacity doubled from 2005 to 2006 and is expected to increase in the future, potentially producing 1.6 percent of China's total electricity generation by 2030. Because of low costs for equipment and land and less stringent investment standards, wind power is expected to have one of the greatest potentials for success among renewable resources. However, for China to expand in wind power technology, investments in grid expansion and transmission upgrades must occur. Aside from wind power, photovoltaic systems accounted for 70 MW of electricity in 2005, of which 50 percent were used for rural, off-grid generation. With cost reductions, solar electricity is expected to rise. Finally, China plans on increasing biomass used for heat and electricity to 110 TWh by 2030. Currently, biomass produces eight TWh (International Energy Agency, 2007).

Non-renewable resources other than coal also play a role in the China's electricity future. Natural gas generation is expected to represent around 4 percent of the total share of China's electricity in 2030. The future of gas is unclear, however, as much of the supply is linked to uncertain development in the domestic market and the fluctuating prices of imports. Oil, conversely, is expected to fall to less than 1 percent by 2030. Finally, nuclear generation, which accounted for 2.1 percent of total generation in 2005, is expected to climb to three percent by 2030, playing a significant role in electricity diversification. Recent efforts have been made to encourage nuclear production. China is pursuing long-term technology development while engaging in independent reactor design and construction (International Energy Agency, 2007).

ECONOMIC FACTORS

The total population of China surpassed 1.32 billion in 2008, accounting for more than 20 percent of the total world population (National Bureau of Statistics of China, 2009). Due to an incredibly high growth rate, population is estimated to reach 1.5 billion by 2035 (Chinese Academy of Social Sciences, 2009). Approximately 45 percent of total population resides in metropolitan areas, where electricity demand is large and supply is generally abundant. About 55 percent of the population resides in rural areas, where infrastructure is poor and the electricity supply is often insufficient and limited (Chinese Academy of Social Sciences, 2009).

China's economy is under rapid development since the "open-door" policy implemented in late 1970s. Currently, China is the third largest economic entity in terms of GDP. China's GDP in 2007 was 24.95 trillion Renminbi (RMB) (equivalent to US$3.7 trillion). On average, each person contributes 18,934 RMB (equivalent to US$2,784) (National Bureau of Statistics of China, 2009). Although the GDP is large, the per capita GDP is very small. Since the 1980s, the GDP has increased each year at 8 percent and is expected to increase even more in the future (The Central People's Government of The People's Republic of China). China's unprecedented pace of economic development will undoubtedly require more energy. World Energy Outlook (2007) estimated that China is likely to overtake the United States, becoming the world's largest electricity consumer by 2010.

Industry consumes more than three quarters of the total electricity generated. Residential consumption accounts for more than 10 percent (National Bureau of Statistics of China, 2009). The World Energy Outlook (2007) estimated that China's electricity demand grows at 5.1 percent per year mainly due to the increase of heavy industry. In the long run, the economy is predicted to mature, with demand slowing. The structure of output shifted toward less energy-incentive activities and it will apply more energy-efficient technologies. As China's economy and population grows, we expect China's electricity demand to increase in the next 20 years.

POLICY

Institutional Framework

Between 1949 and 1978, the Chinese economy was centrally planned, while the electricity industry was a vertically integrated, state-owned utility. Since 1985, however, the power industry has undergone a series of market-oriented, open economy reforms, including the termination of the electricity monopoly (Xu & Chen, 2006). In an attempt to separate government functions from business and encourage market-oriented competition, China split the sole electricity corporation into two transmission companies and five regional generation entities (The Big Five) in 2002 (International Energy Agency, 2007). However, due to a lack of investment in the grid and intergovernmental conflict, shortages developed and the newly formed companies showed little success in initiating market competition (Williams & Kahrl, 2008).

In an effort to improve these drawbacks, the State Electricity Regulatory Commission (SERC) was established in 2003 to share responsibility with China's National Development and Reform Committee (NDRC) in regulating the electricity industry. The NDRC is a powerful Chinese agency that makes influential economic and societal policy recommendations. SERC has since reported slight improvements in pricing and supply increases, though many experts argue adequate competition has yet to exist. Although officially independent from the industry it regulates, SERC retains close ties to the industry, which weakens regulatory control. Furthermore, the NDRC still plays a large role in market pricing, further weakening SERCs regulatory control. Thus, increased independence in SERC would help to open up competitive pricing and enable proper reform mechanisms (Ma & He, 2008).

Short-Term Goals

Since 1953, China has developed a series of five-year plans to address short-term economic goals. Prior five year plans have primarily focused on expanding energy in order to meet economic growth. However,

the most recent plan, the 11th Five Year Plan (ratified in 2006) (The Central People's Government of The People's Republic of China), includes several initiatives that focus on incorporating energy conservation with China's economic development. The five following goals outline the main energy initiatives in the plan: Prioritizing Energy Conservation, Supporting Energy Independence by Relying on Coal, Expanding Energy Resources, Improving the Supply and Demand Relationship, and Encouraging the Development of Nuclear and Renewable Resources(Maede, 2007).

Long-Term Goals

In addition to the 11th Five Year Plan, China also initiated the National Medium and Long-Term Plans for Science and Technology Development in 2006. The framework is based off a series of three stages, which sets up a timeframe to develop a long-term energy development plan. The first phase runs from 2006-2020 and incorporates many of goals developed in 11th Five Year Plan. Phase II, which takes place 2021-2035, focuses on diversifying resources, such as renewable and nuclear energy. Finally, Phase III (2036-2050) ambitiously aims to achieve a sustainable society by significantly reducing the total share of supply of coal to 50percent while increasing renewable and nuclear to 30 percent (Maede, 2007).

Phase I (2006-2020) contains five main energy-related policies: (1) energy conservation, (2) diversification of energy sources, (3) reducing environmental pollution including the use of clean coal, (4) introduction of new energy technology, and (5) safe and reliable power transmission and distribution.

Energy Conservation

The first energy related policy, energy conservation, can be classified into five categories: energy intense targets, the Top 1,000 Enterprises Program, the retiring of inefficient power plants, the closing of inefficient industrial plants, and promoting end-use energy efficiency. First, China aims at "reducing energy intensity (energy consumption per unit of GDP) by 20 percent below 2005 levels by 2010." Second, in 2006, the NDRC targeted 1,000 major companies to promote energy efficiency standards, which include energy supply industries such as electricity. Third, the NDRC plans to shut down small and energy-inefficient plants by 2010. Fourth, the NDRC aims to retire inefficient manufacturing factories. Finally, various energy saving programs for building, industry and consumer goods have been launched based on the 1997 Energy Conservation Law (Pew Center on Global Climate Change, 2007). Additionally, China's energy savings policies for energy intensive products has increased export taxes (2006), set energy intensive targets for all provinces, closed inefficient heavy industry plants, and increased domestic oil prices (International Energy Agency, 2007).

Diversification of Energy Resources

The Renewable Energy Law, enacted in 2006, calls for the mandatory connection of renewable electricity sources to the grid. All utilities must purchase renewable electricity sources and provide adequate grid-connection services and technical support (International Energy Agency, 2007). Furthermore, it "lays out a subsidized tariff structure for electricity generated from renewable energy" (Williams & Kahrl, 2008), encouraging the use of earmarked funding to expand the development of renewable resources. Portions of this funding will be allocated to rural communities (which heavily rely on small-scale hydro, wind, and photovoltaic source) (State Council of the People's Republic of China, 2007).

Reducing Environmental Pollution Including the Use of Clean Coal Technologies

The International Energy Agency's concerns explicitly illustrate the severity of environmental problems in China. "Poor air quality is estimated to impose a welfare cost between 3-8 percent of GDP. The benefits of reducing air pollution would therefore be considerable and can be expected to exceed costs. Environmental pollution has become a growing source of social discontent, and the government recognizes that the costs of neglecting the environment are increasing to unacceptable levels" (International Energy Agency, 2006).

To address increasing emissions, China has ratified both the UN Framework Convention on Climate Change and the Kyoto Protocol as a non-Annex I (developing) country (Pew Center on Global Climate Change, 2007). As a non-Annex I country, China has agreed to develop and use climate friendly technologies, increase public awareness about climate change, and help to improve GHG inventories. Unlike Annex I countries, it does not have specific goals for greenhouse gas reductions. (United Nations Framework Convention on Climate Change, 2009). In 2007, the NDRC issued China's National Climate Change Program which contains objectives, basic principles, key areas of actions and relevant policies and measures to solve the main climate change issues by 2010. The program aims to mitigate greenhouse gases in the energy sector by implementing environmental laws and regulations, reinforcing policies in the energy industry, and improving the development and distribution of suitable technologies (NDRC, 2007).

Safe and Reliable Power Transmission and Distribution

China's energy resources are mainly located in the north and west of the country, but more than half of the total electricity is consumed in the eastern part of the county (Development Trends of China's Electricity Network During the Eleventh Five-Year Period, 2008). China has a goal to create and maintain a unified national power grid through which it can establish market-determined rates for electricity (National Energy Grid, China, 2007). China uses mostly a system of small-scale electricity plants. All of these individual plants contribute to China leading the world in emissions of SO_2 and CO_2. China plans to expand its electricity grid beyond the seven inter-provincial grids it currently uses, reducing these emissions by producing electricity on a regional rather than local scale. The use of a broader grid would result in a global benefit with the reduction of greenhouse gases and acid rain but would have many local environmental benefits including the reduction in the exposure of residents to air pollution (Zhu, Zheng, Guo, & Wang, 2005). Expansion of the grid will enable China to more easily integrate renewable energy sources into its electricity supply (McKinsey&Company, 2009).

ENVIRONMENTAL CONCERNS

Because of China's reliance on coal, they are suffering from serious environmental problems including poor air quality and acid rain. China has seven of the 10 most polluted cities in the world (Beauregard-Tellier, 2007). Respiratory disease is the most common cause of death in urban areas, directly linked to air pollution (Michaelowa, Jusen, Krause, Grimm, & Koch, 2000). These environmental problems impact not only China. The west coast of Canada has seen an increase of more severe storms in the pacific, thought to be the result of sulfur dioxide and particulate emissions from China (Beauregard-Tellier, 2007).

China has prioritized economic growth, making it unlikely that emissions regulations will be put into place. Since China is a developing country (classified as non-Annex I), it does not have greenhouse gas emission targets under the Kyoto Protocol (Beauregard-Tellier, 2007). Across northern China, coal seams burn from small-scale mines, emitting as much carbon dioxide every year as all of the cars in the United States. There is a need for a new development model to reduce the per capita emissions but allow increases in living standards (Watts, 2005).

CONCLUSION

Since there are 200 million people in China living on less than a dollar a day (UNDP International Poverty Centre, September 2004), the Chinese government must make difficult choices between economic development and environmental concerns. Even though the per capita electricity use in China is far less than that of more developed countries, the sheer number of people increases the environmental consequences of electricity decisions made in China on the global scale.

The State Council of China has initiated multiple reforms to encourage sustainability. However, the steep growth rate, coupled with intergovernmental conflict and ineffective regulation has led to electricity reforms falling short (Williams & Kahrl, 2008). For China's sustainable development strategy to be implemented successfully, a greater cooperation between entities must develop. Central governments,

local governments, and private sectors must support energy policies to achieve economic growth, environmental protection, and other social goals. Central governments must also encourage local governments to address energy policies more actively with various economic incentives. Finally, the reorganization of central and local governments is necessary to effectively administer energy policy (Sinton, Stern, Aden, & Levine, 2005).

Electricity production and markets in France have various distinguishing characteristics. First, 78.3 percent of electricity in the country is produced via nuclear generation (International Energy Regulation Network, 2007). This high concentration of nuclear supply yields significantly lower carbon dioxide emissions than other supply technologies, putting France in a competitive position after any climate change legislation or treaty. Secondly, as a participating nation within the European Union (EU), France provides a case study for nations participating in broader political spheres. These cooperating nation states will only become more common with international markets and development of international treaties and agreements to address climate change. Finally, a single company, Electricité de France (EDF), is responsible for 86 percent of electricity generation in the nation, while the national government retains a majority share of the company (International Energy Regulation Network, 2007). Consequently, the market is highly concentrated, both in how electricity is produced and by whom.

THE ELECTRICITY MARKET

France is the second largest electricity market in the European Union (Electricité de France, 2007). The French market is characterized as a developed, industrialized market with minimal population growth, and consequentially little expected growth in electricity demand. French electricity capabilities are unique as it is a world leader in nuclear power generation, electricity exportation, and exportation of nuclear technology. Figure 28 represents French electricity sources as of 2008 (French Ministry of Energy Development, 2007).

France currently operates 59 nuclear power plants of which 34 were constructed in the 1970s and 1980s. While many of these plants are nearing the end of their projected life, an ambitious government plan to modernize France's aging nuclear plants and construct new plants based on improved technologies is already in progress (Bezat, 2007). Nuclear energy will continue to be the primary source of electricity in France over the next 50 years, with some increases in renewable supply as well.
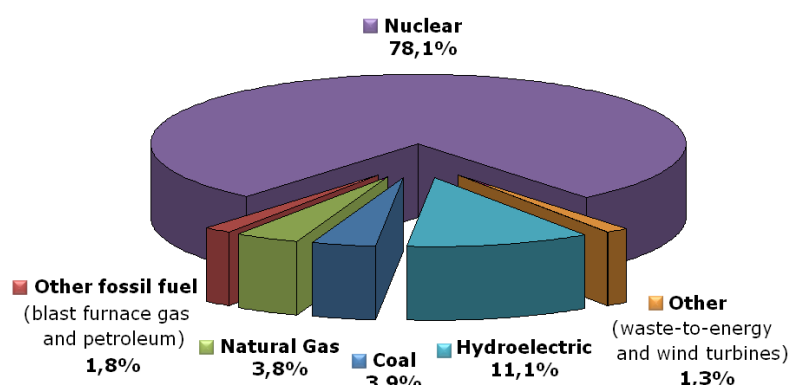
Figure 28: Source of Electricity in France, 2008 (French Ministry of Energy Development, 2007).

ECONOMIC FACTORS

France is the largest net exporter of electricity in the Europe, with 12 percent of production exported (International Energy Regulation Network, 2007). Electricity is France's fourth largest export product contributing significantly to supply available in the European Union (World Nuclear Association, 2008). France shares a competitive advantage in European Union electricity supply due to the inexpensive cost

of production and the EU's stated commitments to reduce greenhouse gas emissions by utilizing low-emission and renewable energy resources (Commission to the European Council and the European Parliament, 2007).

In addition to electricity exports, France is a major exporter of nuclear facility construction technology. The cost of electricity in France is among the lowest in the world, at approximately US$ .0854 per kWh in 2007 (NUS Consulting Group, 2007). The use of a single universal plant type across all 56 nuclear plants built in the 1960s created economies of scale, where costs of equipment, operations, and maintenance could be kept low (Palfreman.) (Palfreman, n.d.)Areva, a French government owned nuclear plant construction company, has developed next generation plant technologies already planned for construction around the globe (Electricité de France, 2007).

Electricité de France (EDF) is responsible for 86 percent of electricity generation within France (International Energy Regulation Network, 2007). EDF originated from the nationalization of numerous private firms in 1946, and remained a national public firm until 2005 (Hoovers). Deregulation has proceeded in the past 10 years in fits and starts, in accordance with European Union rulings (Hoovers).

<center>POLICY</center>

Current Situation

After the oil crisis of the early 1970s, France opted to use nuclear energy as its primary source of electricity. Over the next 15 years, France installed 56 nuclear reactors, satisfying its power needs and even exporting electricity to other European countries (Kouchner, 2008). It did this to ensure its independence and prosperity. Today, France has relative autonomy with approximately 78 percent of electricity needs supported through nuclear power (World Nuclear Association, 2008).

France has two competitive advantages in this field. First, the concentration of nuclear power in France means French engineers, regulators, scientists, and operators have more experience building and operating nuclear facilities than perhaps any others. Second, French engineers have developed a novel reprocessing technique, yielding less radioactive wastes than any other country (Power Struggle: Will France continue to lead the global revival of nuclear power?, 2008).

Domestic Policy

France relies extensively on nuclear in part because it has extremely limited in-state supply of conventional fuels such as coal, oil, or gas. In this context, France aims to maintain steady electricity supply and pricing while maintaining market share in international markets. In addition, the Energy Act of July 13, 2005 also prioritizes taking actions to confront climate change (DGEMP, November 2006). Within this Energy Act are stated priorities to increase the use of renewable energies while sustaining nuclear as a significant source, increasing research, and maintaining electricity transmission systems (DGEMP, November 2006). Specific goals address these priorities. First is a reduction of electricity intensity (the quantity of electricity consumed per person) at least 2 percent per year until 2015, and by 2.5 percent per year until 2030 (DGEMP, November 2006). Additionally, France commits to producing 10 percent of its electricity with renewable technologies by 2010 (DGEMP, November 2006).

International Roles: Energy Policy of the European Union

The EU has clearly identified climate change and increasing fossil fuel prices as primary concerns to be addressed by international policy (DGEMP, 2006). Key goals of European Union policies are to promote further agreements and treaties to address climate change, increase the supply of renewable electricity, increase competition in the supply market, and further partnerships to ensure stable access to electricity with non-EU countries (European Union Commission, 2006).

France is well positioned in its EU role, as a supplier of electricity which is not producing large quantities of carbon dioxide while exporting significant quantities of electricity to neighboring EU countries. In this context, the EU supports France's nuclear energy, even as nuclear producers are closely monitored (European Union Commission, 2006). France has in turn advocated the EU invest further in renewable technology research and development (DGEMP, 2006).

ENVIRONMENTAL CONCERNS

Production of energy from non-fossil fuel based energy has a positive effect on the environment due to a decrease in greenhouse gas production. Other environmental concerns arise, however, regarding the use of nuclear energy such as water requirements and impact on aquatic life, and also long term safe storage of nuclear waste.

Figure 29 shows the change in CO_2 emissions over time in France. This figure illustrates how France has greatly reduced its CO_2 emissions. In fact, France cut its CO_2 emissions by 27 percent in just seven years (Ducroux, 2003). France is one of the leaders in Europe for low CO_2 emissions per capita, (Ducroux, 2003).
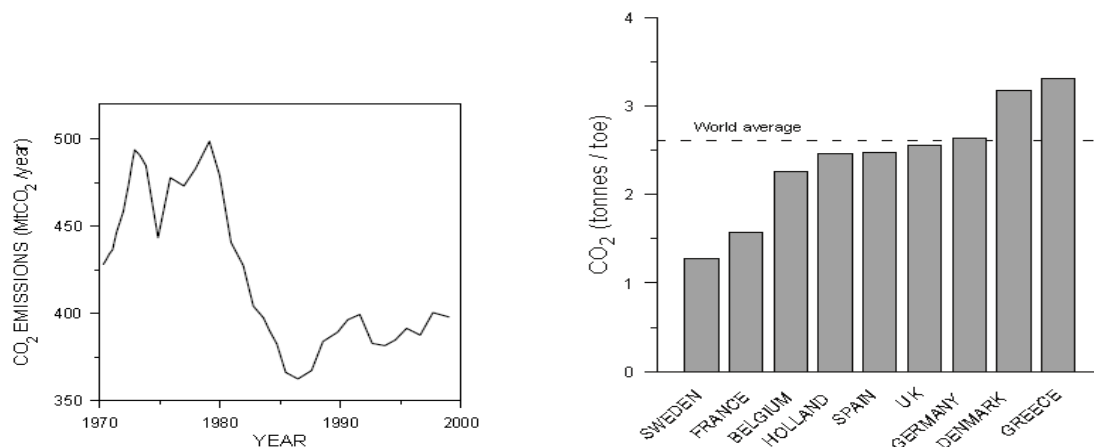
Figure 29: French CO_2 emissions 1970–1999, and CO_2 releases in the European Union by county (Jean-Baptiste and Ducroux, 2003).

Water Use

Nuclear energy facilities use water in cooling towers to reduce heat build-up. This heat is absorbed by the water and then the water is released back into the stream or aquifer from which it came. While there are no contaminants in the water from the nuclear energy production, the water has an elevated temperature, which can impact the stream biota functioning and composition (Lair, 1980). In order to protect ecosystem functioning, temperature limits for the effluent are set.

In France, of the 58 nuclear power plants, 37 are located along rivers and release water into the rivers at elevated temperatures (Godoy, 2006). Recent heat waves caused a spike in energy usage in Europe, which consequently caused blackouts in France because the nuclear power plants could not meet the environmental standards set for elevated water temperature, and were therefore forced to shut down (Parkpoom, 2008). Other power plants were left operating and were releasing water at temperatures higher than what is normally allowable (Godoy, 2006). This is just one example of how environmental regulation coincides with the production of adequate supply of electricity. Such regulation may become more prolific as nations seek to address climate change and carbon dioxide emissions.

Radioactive Wastes

Nuclear energy production creates radioactive waste which must be stored, transported, and disposed. In France, waste disposal is regulated under France's Waste Management Act which was enacted in 1991 and amended in 2006. This act established the direction of future waste disposal research and created a national radioactive waste management agency (ANDRA). Further, in June of 2006 the Nuclear Materials and Waste Management Act was passed. This act states that long lived and high level radioactive wastes require deep geological disposal, and set 2015 as the goal for licensing a repository, and 2025 the goal for opening a repository. This act also supports the reduction of the quantity and toxicity of radioactive wastes through reprocessing and recycling as much as possible. This act requires that a national plan for waste clearly establish solutions, goals, and research plans to reach goals which must be reviewed every three years. (World Nuclear Association, 2008).

CONCLUSION

Overall, France faces relatively steady supply and demand in electricity with an extremely stable population and relatively low externalities for energy generation. Nuclear generation continues to dominate its electricity market, which makes France unique among other countries examined. Carbon regulation will not have a significant impact on French energy policy, which has clearly been a policy with a long-term electricity strategy. From this position, France will be a leader in the EU with regard to energy policy.

There is no question that the US faces a great challenge as it endeavors to meet rising demands for electricity while contending with environmental concerns, security issues and rising energy prices. Continued unease about acid rain and global warming could result in the US passing legislation that would tighten environmental emission standards and will certainly have an impact on electrical utility expansion decisions, prices and supply. The mere prospect that federal carbon legislation will be enacted is already having an effect on utility planning and investment (Chupka, Transforming America's Power Industry: The Investment Challenge 2010-2030, 2008). Continued advances in solar and wind turbine technology could make renewable sources more economical in the future. However, it is unlikely to succeed without assistance from the government, probably in the form of a carbon tax or carbon trading scheme.

Background

The electricity sector in the US lacks a comprehensive national policy framework which is determined by federal, state and local public entities. Many scholars point out that the US electricity industry structure is antiquated and deals with an incompatible mix of state and federal regulation (Bamberger, 2004). The current electric power system in the US is heavily dependent on large, centralized power plants, fossil and nuclear fuels and an increasingly stressed transmission system. Of all the energy consumed in the US, 42 percent is used to produce electricity. Electricity production accounts for 40 percent of all US CO_2 emissions (Joskow, 2008).

Under a "business as usual" scenario total net generation to the grid is expected to increase 24 percent from 3,906 billion kWh in 2006 to 4,854 billion kWh in 2030 (Energy Information Administration, 2009). Demand for electricity is predicted to increase by more than 50 percent by 2025 (Energy Information Administration, 2009). This increasing supply and demand will place even more strain on the United States electricity transmission and distribution system which may lead to decreased system reliability and even widespread blackouts.

There are several significant risks to America's electricity security in the coming years. First, 49 percent of US electricity generation today comes exclusively from coal (Energy Information Administration, 2009). Coal is responsible for some of the most pressing environmental concerns facing our globe today, including climate change, acid rain, mercury, fine particulate matter and environmental damages associated with mining and waste. In addition, 19 percent of US electricity generation comes from nuclear power plants. There is great risk and cost associated with disposing of nuclear waste as well as risks of routine and accidental radionuclide releases and the threat of a major accident (Chupka, Transforming America's Power Industry: The Investment Challenge 2010-2030, 2008). There is also uncertainty over the cost and availability of uranium into the future. Lastly, 18 percent of US electricity generation today comes from natural gas, hydroelectrical and oil power plants, which contribute to air pollution and other environmental problems and are prone to extreme price volatility (Chupka, Transforming America's Power Industry: The Investment Challenge 2010-2030, 2008).

Over the next few decades uses of renewable energy could help to diversify the nation's power supply. Renewable energy encompasses a broad range of technologies that vary considerably. Some technologies such as geothermal and hydropower are mature and economically competitive while others need additional development to become competitive with current technology. Renewable resources (including hydropower) accounts for 8.4 percent of the nation's power supply (Energy Information Administration, 2009). China leads the world in total renewable energy consumption for electricity production, but it is followed closely by the US. The US produces twice as much non-hydro renewable energy for electricity production as Germany and more than three times as much as Japan (Energy Information Administration, 2009).

Demographics

The Census Bureau projects national population to increase from about 310 million in 2010 to about 439 million people in 2050, with annual percentage increases less than one percent and declining each year (Population Division, 2008). Population proves to be a key determinant of demand for electricity. In the absence of political, technological or sector variables, however, population alone may be less helpful in predicting the nature of electricity demand in the future.

Total Demand

Total net generation to the grid is expected to increase 24 percent from 3,906 billion kWh in 2006 to 4,854 billion kWh in 2030 (Energy Information Administration, 2009). The average annual change is about one percent growth each year. As previously stated, the US relies heavily on coal to generate electricity (Figure 30). There is little reason to believe this will change significantly in the future: hovering around 50 percent of electricity generation currently, coal will generate only slightly less than 50 percent of electricity generation in 2030 (Energy Information Administration, 2009). However, EIA projects that renewable-generated electricity will increase from the current 8.4percent to 12.5 percent of total US electricity generation by 2030.

Figure 30. Total Electricity Generation by Fuel (Current and Projected).*Source: EIA, 2009*
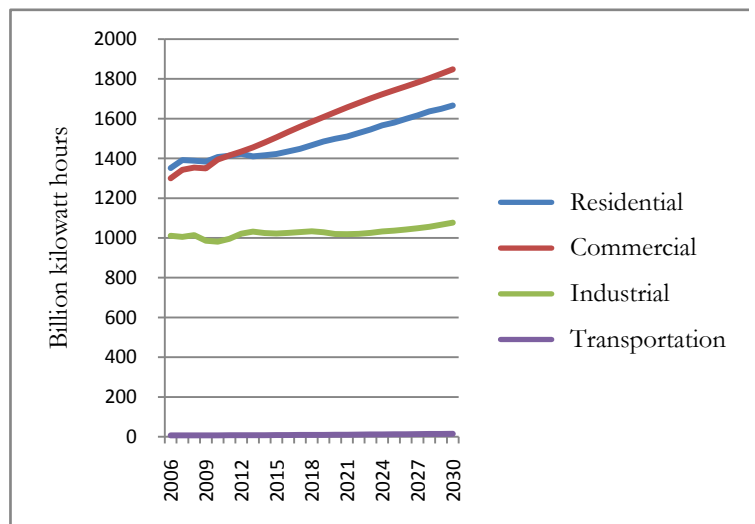
Figure 31. Electricity Sales by Sector (Current and Projected). *Source: EIA, 2009*

Sector Demand

Industrial demand is predicted to remain very stable over the next 20 years (hovering at 1000 billion kWhs), whereas commercial demand will increase from roughly 1300 billion kWh in 2006 to about 1800 billion kWh in 2030. Both the residential and commercial sectors in the United States will see the largest increase in electricity consumption over any other energy source (0.8 percent and 1.4 percent, respectively) whereas the industrial sector will see most growth in coal-to-liquids heat and power as a source of energy (over 32 percent growth). Electricity as a source of energy will grow only 0.3 percent in the US industrial sector (Energy Information Administration, 2009).

Prices

Controlling for inflation by expressing the prices in 2007 cents per kWh, EIA predicts that the end-use prices in the industrial sector will increase from just over US$0.06 in 2006 to about US$0.075 in 2030. Commercial prices will increase from just under US$0.10 in 2006 to just under US$0.11 cents in 2030.
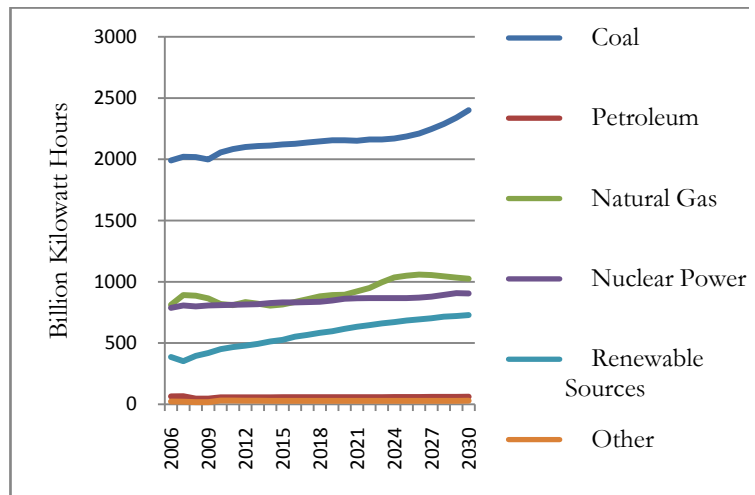
Residential prices, the highest, will increase from just under US$0.11 to over US$0.12 in the same time period (Energy Information Administration, 2009). In terms of prices by service category, generation, transmission and distribution, generation remains the most expensive and increasing (US$0.06 to US$0.07 in the above time period), followed by distribution prices which hover around US$0.025 and even appear to decline by 2030. Transmission prices are the lowest, under US$0.01 for the whole time period (Energy Information Administration, 2009).

COST CONSIDERATIONS

The electric utility sector is increasingly becoming unregulated in the United States. In this environment, cost concerns become the leading determining factor for electricity generating firms (Ansolabehere, 2003). Therefore, the real costs of electricity per kWh of various types of technologies affect companies' considerations about constructing new power plants. For renewable energies to become competitive the real price per kWh must be on par with traditional technologies.

Table 7. Real Levelized Costs of Electricity (cents per kWh)			
Technology	Current Law (As of 2007)	No PTC	No ITC
Nuclear	4.31	5.55	4.31
Conventional coal	3.53	3.53	3.53
Clean coal (IGCC)	3.55	3.55	4.06
Natural gas	5.47	5.47	5.47
Biomass	5.34	5.56	5.34
Wind*	5.70	5.91	5.70
Solar thermal*	12.25	12.25	16.68
Photovoltaics	22.99	22.99	32.60

*Wind and solar technologies require stand-by generation because they are discontinuous power sources, which may raise the cost up to 50 percent. However this cost is not factored into the analysis. Source: (Metcalf, 2007).

Table 7 shows levelized costs[12] of electricity for different technologies in 2004 dollars. In the first column, which considers Production Tax Credits (PTC) and Investment Tax Credits (ITC) provided as of 2007, coal has the lowest costs. Clean coal and nuclear power are the next competitive with traditional coal. Biomass, natural gas and wind are similar and range between US$5.34 and US$5.70 per kWh. The most expensive source is photovoltaics, which is over six times more expensive than coal. If production and investment tax credits are eliminated from the analysis, there is no cost change for conventional coal and natural gas. If just PTC is eliminated, the cost of nuclear raises by nearly 30 percent and that of biomass and wind raises nearly 4 percent. Eliminating ITC raises the cost of the clean coal plant, solar, and photovoltaics by 15 percent, 36 percent, and 42 percent, respectively (Metcalf, 2007).

Lower capital costs, shorter construction times, higher efficiencies, and lower emissions give natural gas an advantage over coal and other fuels for new generation (National Energy Policy Development Group, 2001). For these reasons more than 90 percent of new power plants to be built in the next 20 years will likely to be fueled by natural gas (International Energy Regulation Network, 2007). The Energy Information Administration predicts that natural-gas-fired plants is going to account for 53 percent of

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[12] The key parameters used in levelized cost analysis are operating costs, overnight costs (total capital construction costs), debt finance, capacity factor, construction time, economic life of the plant, production and investment tax credits.

capacity additions until 2030, as compared with 22 percent for renewables, 18 percent for coal-fired plants, and 5 percent for nuclear (Energy Information Administration, 2009).

Supported by tax incentives, renewable generation is predicted to double from 2007 to 2030, reaching a share of more than 14 percent of total electricity generation. Production from nuclear power is predicted to grow by 13 percent from 100.5 GW in 2007 to 112.6 GW by 2030, but its share is predicted to decrease by one percent by 2030 (EIA). Environmental concerns and a scarcity of new large-scale sites limit the growth of conventional hydropower, and from 2007 to 2030 its share remains steady between six percent and seven percent. Wind and biomass is predicted to be the largest sources of electricity among the non-hydropower renewables. Generation from wind power is expected to increase from 0.8 percent of total generation in 2007 to 2.5 percent in 2030, while generation from biomass will grow from 0.9 percent to 4.5 percent (Energy Information Administration, 2009).

TRANSMISSION AND DISTRIBUTION

The challenges to future electricity transmission in the US are twofold: to keep pace with rising demand for electricity and to meet new requirements for renewable resources. Growth in electricity generation has stressed the American transmission systems, resulting in less flexibility to respond to system problems and an increased risk of blackouts. New technologies, such as plug-in hybrid vehicles, will continue to stress grid systems. To meet these needs, the United States must undertake drastic investments in transmission and distribution systems to increase capacity and accommodate growing demand (Chupka, Transforming America's Power Industry: The Investment Challenge 2010-2030, 2008). The Edison Foundation (2008) estimates that the US will need to invest about US$15.5 billion between 2010 and 2030 in undiscounted nominal terms in order to access increasing amounts of progressively more remote renewable. This is considered a conservative estimate.

POLICY

Given rising scientific evidence of global warming dangers and increasing international pressure, it is likely that the United States will move toward regulating carbon dioxide in the coming decade. Any climate change regulations will have a significant impact on the future of electricity production in the United States. Within the US, there is an important debate between those who favor a cap and trade system and those who support a direct tax on the production of CO_2, which comes from coal, oil, and natural gas (Redburn, 2007).

Many scholars agree that cap and trade or taxes are the most effective way to correct the market failure of externalities. There are many attractive similarities between cap-and-trade and taxes for CO_2 regulation. Both reduce emissions by creating a price to associate with emission activities (Parry, 2007). Assigning this price internalizes the externality of carbon dioxide emissions and leads to efficient, low cost reductions. The primary distinction is that taxes generally fix the price of emissions and leave the level of emissions uncertain, while tradable permits fix the level of emissions and leave the price to be determined by the market, assuming firms will trade permits up to the optimal price (Parry, 2007).

Either option will put a price on greenhouse gas emissions and would begin to make the price of fossil fuels reflect their true cost to society (Brune, 2008). There is little dispute however, that there will be substantial costs associated with national climate change policy. It is for this reason that the US has resisted endorsing the Kyoto Protocol. The EPA estimates the price per ton of carbon dioxide in an emissions scheme to be between US$61 and US$83 per ton in 2030, rising to a range between US$159 and US$220 per ton in 2050 (Agency, 2008). Electricity producing firms must incur these costs in addition to the cost of updating their facilities in order to meet the more stringent requirements. Any policy will undoubtedly increase the price of electricity, which will lead to losses in US gross domestic product and decreased employment (Parry, 2007).

It is likely that a carbon tax or cap and trade scheme will start with small reductions. A low price on carbon will cause only modest substitution away from coal and will most likely expand use of natural gas,

with very small incentives for greater renewable use in the short run (Bonacina, 2007). Many would like to see a policy aimed directly at increasing renewables. There have been a number of bills before Congress proposing national renewable portfolio standards ranging from five percent to 20 percent by different deadlines, yet none have been passed into law. These standards would set a minimum limit on the percentage of electricity that must be produced by renewable. A major critique of renewable energy portfolio standards is that they can be costly and are not as efficient as a tax or cap-and-trade scheme (Bonacina, 2007).

In addition, the growth of renewable electricity production in the United States depends in part on the future route of electricity market deregulation and restructuring. A move toward more competitive electricity markets will likely end many regulatory programs that traditionally have supported the use of renewables. However, the move toward competitive retail markets makes it possible for renewable generators to differentiate their product and appeal directly to consumers (Bonacina, 2007). It is important to note that supply-side incentive programs are likely to have a more significant effect than consumer preferences on the demand side (Bonacina, 2007). No matter the ownership system involved, public, private, or cooperative, power companies will all be subject to the same regulations imposed under future carbon policies.

CONCLUSION

When the US adopts a serious policy to constrain CO_2 emissions, the electric power sector will most certainly be a central target. This sector produces 40 percent of America's CO_2 emissions and experts believe that it is the most economical and efficient way to reduce CO_2 emissions in the US. The most efficient sites for renewable energy facilities, especially wind and large solar facilities are often located far from urban centers. To take advantage of these opportunities, the US must make significant investments in new long-distance transmission grid systems. The organizational and regulatory framework that currently governs much of the US electric power sector is not conducive to supporting these transmission investments. Major reforms of America's energy regulatory institutions are needed in order to meet future federal renewable energy portfolio standers.

REFERENCE LIST

Ackermann, T. (2005). *Wind Power in Power Systems.* John Wiley and Sons.

All Business. (2002). Services Sector: its role in world food production and trade. Retrieved February 24, 2009, from http://www.allbusiness.com/management/business-support-services/315977-1.html

Balducci, P. J., Roop, J., Schienbein, L., DeSteese, J., & Weimar, M. (2002). *Electrical Power Interruption Cost Estimates for Individual Industries,Sectors, and U.S. Economy.* Pacific Northwest National Laboratory .

Barry, P. (2008). Greener Green Energy. *Science News , 173* (9), 133-134.

Baxter, R. (2005). *Energy Storage.* PennWell Books.

BBC. (2004). *China's energy supply "dwindling".* Retrieved 2009, from BBC News: file:///G:/Spring%202009/V600/china/china%20energy%20dwindle%20bbc.htm

Beauregard-Tellier, F. (2007). Economics Division. *Parliamentary information and research service .*

Bezat, J.-M. (2007). France trusts in nuclear future. *The Guardian.*

Board on Energy and Environmental Systems . (2008). *What You Need to Know About Energy.* The National Acadamies Press.

British Petroleum Inc. (2007). *BP Statistical Review of World Energy.* Statistical Review.

Brown, M. H., & Sedano, R. P. (2004). *Electricity Transmission.* National Council on Electricity Policy.

Bueno, C., & Carta, J. (2006). Wind powered pumped hydro storage systems,a means of increasing the penetration of renewable energy in the Canary Islands. *Renewable and Sustainable Energy Reviews* , 312-340.

Buigues, G., Zamora, I., Mazon, A. J., Valverde, V., & Perez, F. J. (2006). Sea Energy Conversion: Problems and Possibilities. *Electrical Engineering Department: University of Basque Country* , 1-8.

Carmichael, G. R., Streets, D. G., Calori, G., Amann, M., Jacobson, M. Z., Hansen, J., et al. (2002). Changing Trends in Sulfur Emissions in Asia: Implications for Acid Deposition, Air Pollution, and Climate. *Environmental Science and Technology , 36* (22), 4707-4713.

Cavallo, A. j. (2007). Controllable and affordable utility-scale electricity from intermittent wind resources and compressed air energy storage (CAES). *Energy* , pp. 120-127.

Central People's Government of The People's Republic of China. (2009). Retrieved 2009, from http://english.gov.cn/

Chamia, M. (1999). *HVDC- A major option for the electricity networks of the 21st century.* Sweden: ABB Power Systems.

Chinese Academy of Social Sciences. (2009). Statistical Data (foreign language source). Retrieved on March 1, 2009. <http://www.cass.net.cn>

Chupka, M. R.-P. (2008). Transforming America's Power Industry: The Investment Challenge 2010-2030. *The Edison Foundation .*

Coal and Climate Change Facts. (2009). Retrieved from Pew Center on Global Climate Change: http://www.pewclimate.org/global-warming-basics/coalfacts.cfm

Commission to the European Council and the European Parliament. (2007). *An Energy Policy for Europe.* Retrieved April 5, 2009, from http://europa.eu/scadplus/leg/en/lvb/l27067.htm

Committee on Health and Environmental Effects of Increased Coal Utilization. (1980). Report on Health and Environmental Effects of Increased Coal Utilization. *Environmental Health Perspectives* , 135-153.

Consumer Electronics Association. (2008). *Consumer Research.* Retrieved March 2008, from Consumer Electronics Association: http://www.ce.org/Research/Consumer_Research/276.asp

Crompton, P., & Wu, Y. (2005). Energy consumption in China: past trends and future directions. *Energy Ecomomics 27* , 196.

Demand Side Management Solutions. (2008). Retrieved February 18, 2008, from Demand Side Management Solutions website: www.demandsidemanagement.com

Denholm, P. (2006). Improving the technical, environmental and social performance of wind energy systems using biomass-based energy storage. *Renewable Energy* , pp. 1355-1370.

Denholm, P., Kulcinski, G., & Holloway, T. (2005). Emissions and energy efficiency assessment of baseload wind energy systems. *Environmental Science & Technology* , pp. 1903-1911.

Development Trends of China's Electricity Network During the Eleventh Five-Year Period. (2008). Retrieved 2009, from Market Avenue: http://www.marketavenue.cn/upload/articles/ARTICLES_1227.htm

DGEMP. (November 2006). *France's Energy Situation.* Direction Générale de l'Énergie et des Matières Premières.

DGEMP. (2006). *French memorandum for revitalising european energy policy with a view to sustainable development.* Ministère de l'Économie, des Finances et de l'Industrie,.

Dobson, A., Bradshaw, A., & Baker, A. (1997). Hopes for the Future: Restoration Ecology and Conservation Biology. *Science* , 515-522.

Department of Energy. (2009). *Office of Energy Delivery and Energy Reliability.* Retrieved 2009, from http://www.oe.energy.gov/smartgrid.htm

Department of Energy / National Energy Technology Laboratory. (2007). *Cost and Performance Baseline for Fossil Energy Plants* . National Energy Technology Laboratory .

Dorn, J. (2008). *Data for Solar Thermal Power Coming to a Boil.* Retrieved from Earth Policy Institute: http://www.earth-policy.org/Updates/2008/Update73_data.htm#table1

Dorn, J. (2008). *Solar Thermal Power Coming to a Boil.* Retrieved from Earth Policy Institute: http://www.earth-policy.org/Updates/2008/Update73.htm

Ducroux, J.-B. a. (2003). Energy Policy and Climate Change. *Energy Policy* , 155-166.

Duffield, W. A., & Sass, J. H. (2003). *Geothermal Energy -- Clean Power from the Earth's Heat.* Reston, Virginia: U.S. Geological Survey.

Economist. (2008). Wind of Change. The Economist Print Edition. Retrieved on March 1, 2009. <http://www.economist.com/science/tq/displayStory.cfm?story_id=12673331>

EESD. (2002). *Wave Energy Utilization in Europe: Current Status and Perspectives.* Center for Renewable Energy Sources. < http://www.emu-consult.dk/includes/article.pdf >

Electric Power Research Institute. (2009). *Mercury in the Environment.* Retrieved February 23, 2008, from <http://my.epri.com/portal/server.pt?open=512&objID=387&&PageID=225890&mode=2&in_hi_use rid=2&cached=true>

Electricité de France. (2007). *2007 Annual Report.* Electricité de France.

Energy and Efficiency and Renewable Energy. (2005). Retrieved March 1, 2009, from U.S. Department of Energy : http://www1.eere.energy.gov/windandhydro/hydro_turbine_types.html

Energy Efficiency Standards & Labeling Information Clearinghouse. (2009). Retrieved February 14, 2009, from Energy Efficiency Standards & Labeling Information Clearinghouse Web site: http://www.clasponline.org

Energy Information Administration. (2009). End-Use-Energy Demand (Summary of the Kyoto Report). Retrieved February 24, 2009, from U.S. Energy Administration Administration: http://www.eia.doe.gov/oiaf/kyoto/enduse.html

Energy Information Administration (2007). Retrieved March 2009, from www.eia.doe.gov: http://www.eia.doe.gov/emeu/international/reserves.html

Energy Information Administration. (2009). *Energy Glossary - I.* Retrieved April 23, 2009, from Energy Information Administration: http://www.eia.doe.gov/glossary/glossary_i.htm

Energy Information Administration. (2008). *Annual Energy Outlook 2008 with Projections to 2030 .* Retrieved March 8, 2009, from Energy Information Administration: http://www.eia.doe.gov/oiaf/archive/aeo08/electricity.html

Energy Information Administration. (2009). *US Energy Information Administration/Short-Term Energy Outlook.* Energy Information Administration.

Energy Information Administration. (2008). EIA Annual Energy Outlook 2009 Reference Case Presentation -- December 17, 2008.

Energy Information Administration. (2006). Retrieved February 9, 2009, from International Energy Outlook 2006: www.eia.goe.gov/oiaf/archive/ieo06/electricity.html

Energy Information Administration. (2009). *EIA Annual Energy Outlook 2009.* Energy Information Administration.

Energy Information Administration. (2008). *International Energy Annual 2006, Table 6.2 World Net Electricity Consumption.* Retrieved February 17, 2009, from Energy Information Administration: http://www.eia.doe.gov/emeu/international/electricityconsumption.html

Energy Information Administration. (2007). *Average Price of Coal Delivered to End Use Sector by Census Division and State.* Energy Information Association.

Energy Information Administration. (2008). EIA Annual Energy Outlook 2009 Reference Case Presentation -- December 17, 2008.

Energy Information Administration. (2008). *International Energy Outlook 2008 Highlights.* Retrieved April 26, 2009, from eia.doe.gov: http://www.eia.doe.gov/oiaf/ieo/highlights.html

Energy Policy Act of 1992. (1992). Retrieved February 22, 2009, from Energy Information Administration:
http://www.eia.doe.gov/oil_gas/natural_gas/analysis_publications/ngmajorleg/enrgypolicy.html

Electric Power Research Institute -Department of Energy (EPRI-DOE). (2003). *EPRI-DOE handbook of energy storage for transmission and distribution applications.* Washington, DC.: CA and the US Department of Energy.

European Climate Exchange. (2009). *About ECX.* Retrieved April 20, 2009, from European Climate Exchange Web site: http://www.ecx.eu/About-ECX

European Photovoltaic Industry Association & Greenpeace. (2008). *Solar Generation V - 2008.*

European Union Commission. (2006). *External Energy Relations - From Principles to Action.* Brussels: European Union.

Family, Afrooz. (2005). Hydroelectric Dams. Mad Physics. Retrieved March 1, 2009. <http://www.madphysics.com/ask/dam/>

Fischer, C., Herrnstadt, E., & Morgenstern, R. (2008). *Understanding Errors in EIA Projections of Energy Demand.* Washington, DC: Resources for the Future.

Forbes. (2008). *China Energy-Supply Shortages Continue.* Retrieved 2009, from Forbes: <http://www.forbes.com/2008/08/01/china-energy-oil-biz-cx_0804oxford.html>

Forsund, F. R. (2007). *Hydropwer Economics.* Springer US.

Franco, G. a. (2006). *Electricity Demand and Climate Change in California.*

Franco, G., & Sanstad, A. H. (2006). *Climate Change and Electricity Demand in California* (Vol. White paper). California Climate Change Center.

French Ministry of Energy Development. (2007). *L'Electricité en France en 2007 : une analyse statistique.*

General Electric. (2009). 3.6 MW Series Wind Turbine. Retrieved on March 1, 2009. <http://www.gepower.com/prod_serv/products/wind_turbines/en/36mw/index.htm>

Gira Solar Turkey Ltd. (2005). Turkey Adopts National Feed-in Law for Renewables. Retrieved on March 3, 2009. <http://www.girasolar.com.tr/content.php?id=7>

Godoy, J. (2006). *IPS news.* Retrieved April 9, 2009, from Environment: Heat Wave Shows Limits of Nuclear Energy: http://ipsnews.net/news.asp?idnews=34121

Goodell, J. (2006). *U.S. Climate Change Politics from Below.* International Studies Association .

Gotham, Douglas. (2009). State Utility Forecasting Group. (Indiana) Presentation in March of 2009.

Hamilton, K. a. (2007). *Voluntary carbon markets: an international business guide to what they are and how they work.* Published by Earthscan.

Hammons. (2000). Role of HVDC Transmission in Future Energy Development. *Power Engineering Review*.

Hammons, T. D. (2000). Role of HVDC Transmission in Future Energy Development. *IEEE Power Engineering Review* , 10-25.

Holl, K. (2002). Long-term Vegetation Recovery on Reclaimed Coal Surface Mines in the Eastern USA. *Journal of Applied Ecology* , 960-970.

Hoovers. (2009). *Electricité de France: History*. Retrieved April 5, 2009, from http://premium.hoovers.com/subscribe/co/history.xhtml?ID=ffffstcfttkhthjjct

Hutton, T. A. (2004). Service industries, globalization, and urban restructuring within the Asia-Pacific: new development trajectories and planning responses. *Progress in Planning , Volume 62* (Issue 1), 67.

International Atomic Energy Agency. (2001). *Analysis of Uranium Supply to 2050*. Vienna: IAEA.

Idaho National Laboratory. (2005). *Hydropower*. Retrieved 2009, from http://hydropower.inel.gov/hydrofacts/pdfs/01-ga50627-01-brochure.pdf

Intergovernmental Panel on Climate Change. (2007). *IPCC, 2007: Summary for Policymakers*. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.

International Energy Agency. (2008). *Key World Energy Statistics*. Paris: IEA.

International Energy Agency. (2005). IEA Hydro: IEA Hydropower Implementing Agreement. Retrieved March 2, 2009. <http://www.ieahyrdo.org/agreement.htm>

International Energy Agency. (2007). *Combustible Renewables and Waste*. Retrieved from International Energy Agency: http://www.iea.org/Textbase/stats/defs/sources/renew.htm

International Energy Agency. (2005). *Projected Costs of Generating Electricity: 2005 Update*. Paris: OECD/IEA.

International Energy Agency. (2007). *Renewables in Global Energy Supply*. Paris: OECD/IEA.

International Energy Agency. (2007). *World Energy Outlook 2007*. Paris: OECD.

International Energy Agency. (2007). *World Energy Outlook 2007, China and India Insights*. France: OECD/International Energy Agency.

International Energy Agency. (2008). *World Energy Outlook*. IEA/OECD.

International Energy Agency, O. (2006). *China's Power Sector Reforms: Where to Next?* Paris: OECD, IEA.

International Energy Regulation Network. (2007). *Country Factsheets: France*. Retrieved April 5, 2009, from http://www.iern.net/portal/page/portal/IERN_HOME/COUNTRY_FACTSHEETS/COUNTRY_F ACTSHEET?pId=3070021&pPath1=Europe&pPath2=France

International Hydropower Association. (2005). *Hydro's Contribution*. Retrieved from International Hydropower Association: http://www.hydropower.org/downloads/F1_The_Contribution_of_Hydropower.pdf

International Hydropower Association. (2005). *International Hydropower Association: Hydro's Contribution.* Retrieved January 25, 2009, from International Hydropower Association: http://www.hydropower.org/downloads/F1_The_Contribution_of_Hydropower.pdf

International Hydropower Association; International Commission on Large Dams; International Energy Agency; Canadian Hydropower Association. (2000). *Hydropower and the World's Energy Future.*

Intergovernmental Panel on Climate Change. (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage.* New York : Cambridge University Press.

Ishiguro, M., & Akiyama, T. (1995). *Electricity Demand in Asia and the Effects on Energy Supply and the Investment Environment.* Washington, D.C.: The World Bank.

Jones, P. B. (2007). From Generation to Grid. *Renewable Energy Focus* , 38-42.

Kale, S. S. (2004). The Politics of Policy Change in India's Electricity Sector. *Pacific Affairs* , 467-491.

Kirby, N. L. (2002). HVDC Transmission for Large Offshore Wind Farms. *Power Engineering Journal* .

Kirschen, D. S., & Strbac, G. (2004). *Fundamentals of Power System Economics.* John Wiley and Sons.

Knittel, C. (2003). Market Structure and the Pricing of Electricity and Natural Gas. *Journal of Industrial Economics* .

Kouchner, M. B. (2008). Making a successful transition to the new nuclear era. *Les Echos newspaper* .

Kruger, P. (2004). Appropriate Technologies for Large-Scale Production of Electricity and Hydrogen Fuel . *International Journal of Hydrogen Energy* , 5881-5886 .

Kruger, P. (2005). *Electric Power Required in the World by 2050 with Hydrogen Fuel Production – Revised.* International Journal of Hydrogen Energy.

LaCommare, K. H., & Eto, J. H. (2006). *Cost of Power Interruptions to Electricity Consumers in the United States.* California: Lawrence Berkeley National.

Lair, N. (1980). The Rotifer Fauna of the River Loire (France), at the level of nuclear power plants. *Hydrobiologia* , 153-160.

Ledin, M., & Pedersen, K. (1996). The environmental impact of mine wastes - Roles of microorganisms and their significance in treatment of mine wastes. *Earth-Science Reviews* , 67-108.

Legge, C. E. (2003). *Emissions Trading in Europe - Conditions for Environmental Credibility and Economic Efficiency.* Center for European Policy Studies.

Lieberman-Warner Climate Security Act 2008. (2008). Retrieved April 25, 2009, from Joe Lieberman, United States Senator Web site: http://lieberman.senate.gov/documents/lwcsaonepage.pdf

Lijesen, M. G. (2007). The real-time price elasticity of electricity. *Energy Economics* , *29* (2), 249-258.

Ma, C., & He, L. (2008). From state monopoly to renewable portfolio: Restrucutring China's electricity utility. *Energy Policy* , 1697–1711.

Maede, S. (2007). China's Environmental and Energy Problems and the Possibility of Japan-China Techincal Cooperation. *Science & Technology Trends* , 76-85.

Markvart, T. (1994). *Solar Electricity.* (T. Markvart, Ed.) West Sussex, England: John Wiley & Sons Ltd.

Martinez-Gallardo, M. V. (2007). Political Competition and Policy Adoption: Market Reforms in Latin American Public Utilities. *American Journal of Political Science Vol. 51 No.1* , 120-139.

Massachusetts Institute of Technology. (2007). *The Future of Coal: Options for a Carbon-Constrained World.* Boston: MIT. <http://web.mit.edu/coal/>

Massachusetts Institute of Technology. (2006). *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century.* Massachusetts Institute of Technology.

Massachusetts Institute of Technology. (2003). *The Future of Nuclear Power.* Massachusetts Institute of Technology.

McFarland, H. &. (2001). *Energy, Physics and the Environment.* Stamford: Thomson Learning.

McKinsey&Company. (2009). *China's Green Revolution: Prioritizing Technologies to Achieve Energy and Environmental Sustainability.* Australia: McKinsey&Company.

Michaelowa, A., Jusen, A., Krause, K., Grimm, B., & Koch, T. (2000). CDM prejects in China's energy supply and demand sectors- opportunities and barriers. *Hamburgisches Welt-Wirtschafts-Archiv (HWWA) Hamburg Institute of International Economics* .

Mukherjee, A. B., Zevenhoven, R., Bhattacharya, P., Sajwan, K. S., & Kikuchi, R. (2008). Mercury flow via coal and coal utilization by-products: A global perspective. *Resources, Conservation and Recycling* , 571-591.

National Academies Summit on America's Energy Future, 2. (2008). Washington D.C.: National Academies Press.

National Bureau of Statistics of China. (2009). Statistical Data (foreign language source). Retrieved on March 1, 2009. <http://www.stats.gov.cn>

National Energy Grid, China. (2007). Retrieved 2009, from GENI Global Energy Network Institute: http://www.geni.org/globalenergy/library/national_energy_grid/china/index.shtml

National Renewable Energy Laboratory. (2009). *Solar Maps.* Retrieved February 18, 2009, from National Renewable Energy Laboratory: http://www.nrel.gov/gis/solar.html#collector

National Renewable Energy Laboratory. (2007). *United States Annual Average Wind Power.* Retrieved 2009, from National Renewable Energy Laboratory: http://rredc.nrel.gov/wind/pubs/atlas/maps/chap2/2-01m.html

Natural Gas Supply Association. (2009). Retrieved from http://www.naturalgas.org

National Development and Reform Commission. (2007). *China's National Climate Change Program.* Beijing: National Development and Reform Commission.

Nelson, P. A., Behrens, D., Castle, J., Crawford, G., Gaddam, R. N., Hackett, S. C., et al. (2008). *Developing Wave Energy in Coastal California: Potential Socio-Economic And Environmental Effects.* California Energy Commission, PIER Energy-Related Environmental Research Program & California Ocean Protection Council CEC-500-2008-083.

NETL/Department of Energy. (2008). *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements 2008 Update.*

NUS Consulting Group. (2007). 2006-2007 International Electricity Report & Cost Survey. New York, New York.

Office of Air and Radiation. (2001). *Electricity Demand Response to Changes in Price in the EPA's Power Sector Model.* Environmental Protection Agency.

OKSolar (2009). *World Daily Insolation Map.* Retrieved on March 2, 2009 from OKSolar.com: http://www.oksolar.com/abctech/solar-radiation.htm

Palfreman, J. (2009). *Why the French Like Nuclear Energy.* Retrieved April 5, 2009, from http://www.pbs.org/wgbh/pages/frontline/shows/reaction/readings/french.html

Parkpoom, S. (2008). Analyzing the Impact of Climate Change on Future Electricity Demand in Thailand. *IEEE Transactions on Power Systems, vol. 23, no. 3* , pp. 1441-1448.

Petroleum, B. (2008). *British Petroleum.* Retrieved February 20, 2009, from Ethanol Statistical Review: http://www.bp.com/sectiongenericarticle.do?categoryId=9023791&contentId=7044194

Pew Center for Climate Change. (2008). Climate Change 101 Cap & Trade. Arlington, VA, U.S.A.

Pew Center on Global Climate Change. (2007). *International: Brief: China-Mitigation.* Retrieved April 12, 2009, from Pew Center on Global Climate Change: http://www.pewclimate.org/international/brief/china-mitigation/042007

Polemis, M. L. (2007). *Modeling industrial energy demand in Greece using cointegration techniques* (Vol. 35). Athens: Energy Policy.

Power Struggle: Will France continue to lead the global revival of nuclear power? (2008). *The Economist* .

Power, M.-A. C. (2006). *Patterson Farms: 250 kW CHP Application.* College Park, MD: Mid-Atlantic Combined Heating and Power.

Regional Greenhouse Gas Initiative. (2009). *Regional Greenhouse Gas Initiative Home page.* Retrieved 04 27, 2009, from http://www.rggi.org/home

Rudervall, R. (2000). High Voltage Direct Current (HVDC) Transmission Systems. *Energy Week 2000* .

Rudervall, R. J. (2000). High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper. *Presented at Earth Week.* Washington D.C.

Ruth, M., & Lin, A. (2006). Regional Energy Demand and Adaptations to Climate Change: Methodology and application to the state of Maryland, USA. *Energy Policy* , 2820-2833.

Saghir, J. (2005). *Energy and Poverty: Myths, Links, and Policy Issues.* The World Bank Group: Energy and Mining Sector Board.

Simon, C. (2007). *Alternative Energy: Political, Economic, and Social Feasibility.* Lanham, MD: Rowman & Littlefield Publishers, Inc.

Sinton, J. E., Stern, R. E., Aden, N. T., & Levine, M. D. (2005). *Evaluation of China's Energy Strategy Option.* China Sustainable Energy Program.

Smil, V. (2003). *Energy at the Crossroads: Global Perspectives and Uncertainties.* Cambridge, MA: The MIT Press.

Sokolov, Y. M. (2006). *Nuclear Power – Global Status and Trends.* Retrieved 2009, from http://www.iaea.org/OurWork/ST/NE/Pess/assets/nuclear_energy_Alan_Sokolov06.pdf

State Council of the People's Republic of China. (2007). *China's Energy Conditions and Policies.* n.a.: n.a.

Stern, L. (2005). *Office of Climate Change.* Retrieved from http://www.occ.gov.uk/activities/stern.htm

Stern, N. (2005). *Stern Review on the Economics of Climate Change.* Retrieved April 20, 2009, from HM Treasury: http://www.hm-treasury.gov.uk/stern_review_report.htm

Succar, S., & Williams, R. H. (2007). Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation. *Energy Policy* , pp. 1474-1492.

Tennessee Valley Authority. (2009). *Hydrolectric Power.* Retrieved March 6, 2009, from Tennessee Valley Authority: http://www.tva.gov/power/hydro.htm

Thomas, I. (2007). *The Pros and Cons of Solar Power.* The Rosen Publishing Group.

Thorpe, T. W. (1999). An Overview of Wave Energy Technologies: Status, Performance and Costs. *Wave Power: Moving Towards Commercial Viability* , 1-16.

Tsoutsos, T., Frantzeskaki, N., & Gekas, V. (2005). Environmental Impacts from the Solar Energy Technologies. *Energy Policy , 33*, 289-296.

UNDP International Poverty Centre. (September 2004). *In Focus.* United Nations Development Programme. http://www.undp-povertycentre.org/pub/IPCPovertyInFocus4.pdf

U.S. Department of Energy. (2009). Retrieved February 12, 2009, from http://www.energy.gov, http://www.energysavers.gov/financial_assistance.html, http://www.energytaxincentives.org/.

U.S. Department of Energy. (2006). *National Electric Transmission Congestion Study.* US Department of Energy.

U.S. Department of Energy. (2006). *Energy Efficiency and Renewable Energy.* Retrieved April 2009, from Geothermal Technologies Program: http://www1.eere.energy.gov/geothermal/geomap.html

U.S. Department of Energy. (2008). Solar Energy Technologies Program: Linear Concentrators Research and Development. Retrieved on February 27, 2009. <http://www1.eere.energy.gov/solar/linear_concentrator_rnd.html>

U.S. Department of Energy - Energy Efficiency and Renewable Energy Network. (2009). *CSP Technologies Overview.* Retrieved on March 1, 2009, from Concentrating Solar Power and Sun Lab: http://www.energylan.sandia.gov/sunlab/overview.htm

U.S. Department of Energy - Energy Efficiency and Renewable Energy. (2007). *Tribal Energy Program - Guide to Tribal Energy Development.* Retrieved from U.S. Department of Energy - Energy Efficiency and Renewable Energy: http://www1.eere.energy.gov/tribalenergy/guide

U.S. Department of Energy. (2009). *A Consumer's Guuide to Energy Efficiency and Renewable Energy: Your Home.* Retrieved March 6, 2009, from U.S. Department of Energy; Energy Efficiency and Renewable Energy: http://apps1.eere.energy.gov/consumer/your_home/electricity/index.cfm/mytopic=11050

U.S. Department of Energy. (2008). *Geothermal Tomorrow: 2008*. U.S. Department of Energy.

U.S. Department of Energy. (2006). *Ocean Energy Technology Development*. National Renewable Energy Laboratory.

U.S. Department of the Interior. (2006). *Wave Energy Potential on the U.S. Outer Continental Shelf*. U.S. Department of the Interior.

U.S. Department of the Interior, Bureau of Reclamation. (2005). *Reclamation: Managing Water in the West - Hydrolectric Power*. n.a.: n.a.

U.S. Environmental Protection Agency. (2008). *Chief Causes of Concern (NOx)*. Retrieved February 23, 2009, from U.S. Environmental Protection Agency: www.epa.gov/air/urbanair/nox/chf.html

U.S. Environmental Protection Agency. (2007). *What is Acid Rain?* (U. E. Agency, Producer) Retrieved February 22, 2009, from U.S. Environmental Protection Agency: www.epa.gov/acidrain/what/index.html

U.S. Environmental Protection Agency. (2008). *EPA Analysis of the Lieberman-Warner Climate Security Act of 2008*. Retrieved April 25, 2009, from Environmental Protection Agency Web site: http://www.epa.gov/climatechange/downloads/s2191_EPA_Analysis.pdf

U.S. Environmental Protection Agency. (2009). *Clean Air Markets*. Retrieved from Environmental Protection Agency: http://www.epa.gov/airmarkt/

U.S. Geological Survey. (2003). *Geothermal Energy: Clean Power from the Earth's Heat*. Reston, Virginia: USGS.

U.S. Geological Survey. (2008). Hydroelectric Power: How it Works. Retrieved on March 1, 2009. <http://ga.water.usgs.gov/edu/hyhowworks.html>

United Nations Environment Programme Chemicals Branch. (2008). *The Global Atmospheric Mercury Assessment: Sources, Emissions and Transport*. Geneva: UNEP-Chemicals.

United Nations Framework Convention on Climate Change. (1997). *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Kyoto: United Nations Framework Convention on Climate Change.

United Nations Framework Convention on Climate Change. (2009). Retrieved 2009, from Kyoto Protocol: http://unfccc.int/2860.php

United Nations Framework Convention on Climate Change. (2009). *Kyoto Protocol*. Retrieved April 24, 2009, from United Nations Framework Convention on Climate Change Web site: http://unfccc.int/kyoto_protocol/items/2830.php

United Nations. (2008). *World Urbanization Prospects, The 2007 Revision*. New York: United Nations.

United Nations. (2009). *Water in a Changing World*.

United States Congress. (2009). *American Recovery and Reinvestment Act of 2009* . Retrieved April 25, 2009, from THOMAS.loc.gov: http://thomas.loc.gov/cgi-bin/query/D?c111:8:./temp/~c111UX7DjG::

University of Strathclyde Physics and Applied Physics Semiconductor Spectroscopy and Devices. (2009). Retrieved March 1, 2009, from http://level2.phys.strath.ac.uk/SolarEnergy/reading/?photovoltaic

van der Linden. (2006). Bulk energy storage potential in the USA, current developments and future prospects. *Energy* , pp. 3446-3457.

Van Raaij, W. F. (1981). A Behavioral Model Of Residential Energy Use. *Journal of Economic Psychology* , 119-143.

Violette, D., Freeman, R., & Neil, C. M. (2006). *DRR Valuation and Market Analysis Volume 1 Overview.* Demand Response Coordinating Committee.

Watson, R. T., Zinyowera, M. C., & Moss, R. H. (1996). *Technologies, Policies and Measures for Mitigating Climate Change.* Intergovernmental Panel on Climate Change.

Watts, S. (2005). *A coal-dependent future?* Retrieved 2009, from BBC News: file:///G:/Spring%202009/V600/china/coal%20dependent%20future.htm

Whittington, H. W. (2002). Electricity generation: Options for reduction in carbon emissions. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences* , 1653-1668.

Williams, J. H., & Kahrl, F. (2008). *Electricity reform and sustainable development in China.* n.a.: IOP Publishing.

Wiser, R., Barbose, G., & Peterman, C. (2009). *Tracking the Sun: The Installed Cost of Photovoltaics in the U.S. from 1998-2007.* Lawrence Berkeley National Laboratory.

Woodford, D. (1998). *HVDC Transmission.* Winnipeg: Manitoba HVDC Research Centre.

World Bank Development Prospects Group. (2007). *Global Economic Prospects 2007: Managing the Next Wave of Globalization.* Washington D.C.: The International Bank for Reconstruction and Development.

World Bank Development Prospects Group. (2009). *Global Economic Prospects 2009: Commodities at the Crossroads.* Washington, D.C.: The International Bank for Reconstruction and Development.

World Bank Group. (2004). *Proportion of population below $1 (PPP) per day.* Retrieved April 24, 2009, from Millennium Development Goals: http://ddp-ext.worldbank.org/ext/GMIS/gdmis.do?siteId=2&contentId=Content_t1a&menuId=LNAV01HOME1

World Bank. (2009). *Swimming against the tide: How developing countries are coping with the global crisis.* Retrieved March 8, 2009, from World Bank Web site: http://siteresources.worldbank.org/NEWS/Resources/swimmingagainstthetide-march2009.pdf

World Energy Council. (2007). *Survey of Energy Resources 2007.* World Energy Council.

World Health Organization: Europe. (2005). Particulate Matter Air Pollution: How it Harms Health. *Fact Sheet Euro/04/05* . Berlin, Copenhagen, Rome: World Health Organization: Europe.

World Nuclear Association. (2008). *Nuclear Power in France.* Retrieved April 5, 2009, from http://www.world-nuclear.org/info/inf40.html

World Nuclear Association. (2009). *Nuclear Power Reactors.* Retrieved April 20, 2009, from World Nuclear Association Web sit: http://www.world-nuclear.org/info/inf32.html

World Wide Fund for Nature; World Resources Institute. (2004). *Rivers at Risk: Dams and the future of freshwater ecosystems.* Godalming: Panda House, Weyside Park.

Xu, S., & Chen, W. (2006). The Reform of electricity Power Sector in the PR of China. *Energy Policy* , 2455-2465.

Zhu, F., Zheng, Y., Guo, X., & Wang, S. (2005). Environmental impacts and benefits of regional power grid interconnections for China. *Energy Policy , 33* (14), 1797-1805.

COST MODEL INPUTS FOR FOSSIL FUEL/NON-FOSSIL FUEL ELECTRICITY GENERATION TECHNOLOGIES

Fossil Fuel Generation Technology Cost Model Inputs[a]						
Plant Type	PC	PC+CCS	NGCC	NGCC+CCS	IGCC	IGCC+CCS
Capital Cost* ($/kW)	$1,562	$2,883	$554	$1,172	$1,841	$2,496
Thermal Efficiency (%)	38.00%	26.00%	50.80%	43.70%	39.50%	32.10%
Capacity Factor	85%	85%	85%	85%	85%	85%
CO2 Emissions (kg/kWh)	0.776097	0.09979	0.3615131	0.042184100	0.830074	0.1206556
Annual Fixed O & M ($/kW)	$24.92	$37.49	$9.82	$16.64	$35.20	$44.59
Variable O & M (mills/kWh)	4.94	9.16	1.32	2.56	6.39	8.21

Source:

[a] Department of Energy/National Energy Technology Laboratory. *Cost and Performance Baseline for Fossil Energy Plants* , Vol. 1, DOE/NETL-2007/1281, May 2007

Non-Fossil Fuel Generation Technolgy Cost Model Inputs							
Plant Type	Nuclear	Hydroelectric	Geothermal	Wind (On-Shore)	Wind (Off-Shore)	Photovoltaic	Concentrated Solar
Capital Cost* ($/kW)	$2,000[e]	$2,038[a]	$2,500[g]	1797[a]	3416[a]	$5,750[a]	$1,778[a]
Heat Rate (Btu/kWh)	10474[a]		34633[b]				
Capacity Factor	85%[c]	56%[b]	90%[b]	30%[d]	40%[b]	21%[b]	25%[h]
Annual Fixed O & M ($/kW)	$90.02[a]	$13.63[a]	$164.64[a]	$30.3[a]	$89.48[a]	$11.68[a]	$56.78[a]
Variable O & M (mills/kWh)	0.49[a]	2.43[a]	0[a]	0[a]	0[a]	0[a]	0[a]

Sources:

[a] DOE/EIA Report # 0556 (2009). *Electricity Market Module* (http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/electricity.pdf)

[b] DOE/EIA Report# 0556 (2009) *Renewable Fuels Module* (http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/renewable.pdf)

[c] MIT The Future of Nucler Power, 2003

[d] World Bank Report, *Study of Equipment Prices in the Power Industry* , June 2008 draft.

[e] The DOE/EIA Electricity Market Module reports a captial cost of $2,873/kW while the World Nuclear Association reports lower capital costs closer to $1,500-$1,800 (http://www.world-nuclear.org/info/inf02.html)

[g] The DOE/EIA Electricity Market Module reports a capital cost of $1,630; however, the DOE report *Geothermal Tomorrow: 2008* suggests capital cost closer to $4,000

[h] Based on information provided by the DOE, concentrated solar capacity factors absent energy storage are typically 25%. (http://apps1.eere.energy.gov/states/alternatives/csp.cfm)

Methodology for calculating electricity generation technology costs

All generation technologies were evaluated at 500MW capacity with a 40-year operating life. Annual capital costs for all generation technologies were calculated by multiplying the $/kW$_e$ by the 500MW capacity and annuitized over a 40-year operating life using a 10% interest rate. All cost figures are reported in US$2007. Annual operating hours were calculated from the reported capacity factors. Annual capital costs were then divided by annual operating hours to levelize the capital cost per kWh. Reported thermal efficiencies were used to calculate heat rate for fossil fuel plants. For other thermoelectric power plants the heat rate was taken from the literature. Fuel cost per kWh was calculated using the fuel price and heat rate when applicable. The baseline cost of electricity in $/kWh is the sum of reported annual fixed operating costs, variable operating and maintenance costs, levelized capital cost, and fuel costs where applicable.

Methodology for calculating carbon capture/sequestration costs

The methodology for calculating the cost of carbon capture and sequestration was adapted from Giovanni and Richards, 2009 Draft: "Determinants of the Costs of Carbon Capture and Sequestration for Expanding Electricity Generation Capacity." Contact kenricha@indiana.edu for further information. Emissions rates and capture efficiency, assumed to be 90 percent, came from the DOE/NETL Cost and Performance Baseline for Fossil Fuel Plants, 2007. Carbon dioxide transport and sequestration costs were calculated using the following pipeline cost formula reported by McCollum, David. (2006) "Comparing Techno-Economic Models for Pipeline Transport of Carbon Dioxide." Institute of Transportation Studies:

$$Pipeline\ Capital\ Cost = 10822.7 * (Metric\ Tons\ of\ Carbon\ Dioxide\ per\ Day)^{0.35} * (Distance)^{0.13} * (Distance)$$

Pipeline distance was assumed to be 50km. Capital costs were annuitized using the same operating life and interest rate assumptions as for the generation technologies. Annual operating and maintenance costs were assumed to be 3 percent of annual capital costs. Storage reservoir was assumed to be a saline aquifer with a storage cost of US$13.24 adjusted to 2007 dollars from "Economic Evaluation of CO2 Storage and Sink Enhancement Options: Final Technical Report." The additional cost per kWh of carbon dioxide transport and storage was added to the baseline cost of electricity where applicable.

Incremental costs associated with carbon price were calculated from the reported carbon emissions per kWh. The carbon footprint associated with non-fossil fuel generation technologies was not included. The total cost of electricity is the sum of baseline cost, transport and storage cost, and emissions cost. Cost curves were derived by iterating the carbon price between US$0 to US$100 and recording the associated cost of electricity. Finally, the carbon price at technology transfer points was calculated using the following formula as reported in the IPCC Special Report on Carbon Capture and Sequestration, 2005:

$$\frac{(Cost\ of\ Electricity\ Technology\ A) - (Cost\ of\ Electricity\ Technology\ B)}{(Emission\ per\ kWh\ Technology\ B) - (Emissions\ per\ kWh\ Technology\ A)}$$

Sources consulted

Bock, Bert et. al. (2003). "Economic Evaluation of CO2 Storage and Sink Enhancement Options: Final Technical Report" Retrieved from: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=826435

Giovanni, Emmy & Richards, Kenneth. (2009). Draft: "Determinants of the Costs of Carbon Capture and Sequestration for Expanding Electricity Generation Capacity." Contact kenricha@indiana.edu for further information.

Intergovernmental Panel on Climate Change. (2005). Special Report on Carbon Capture and Storage. Retrieved from: http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm.

McCollum, David. (2006). "Comparing Techno-Economic Models for Pipeline Transport of Carbon Dioxide" Institute of Transportation Studies.

TECHNOLOGY TRANSFER CARBON PRICES

Carbon Price Intersections:

- Coal Price $1.60/MMbtu
- Natural Gas Price: $4.50/MMBtu
- Uranium Price: $0.50/MMBtu

Carbon Price Technology Indifference Points (COE1-COE2)/(Emissions2-Emissions1)/100					
	PC	**PC+CCS**	**NGCC**	**NGCC+CCS**	**IGCC**	**IGCC+CCS**
PC		$59.52	-$8.76	$22.63	-$113.32	$47.96
PC+CCS	$59.52		$167.68	-$410.46	$46.75	$422.77
NGCC	-$8.76	$167.68		$63.39	-$20.80	$145.58
NGCC+CCS	$22.63	-$410.46	$63.39		$13.32	-$188.90
IGCC	-$113.32	$46.75	-$20.80	$13.32		$35.69
IGCC+CCS	$47.96	$422.77	$145.58	-$188.90	$35.69	

	Nuclear	**Hydroelectric**	**Geothermal**	**Wind (On-Shore)**	**Wind (Off-Shore)**	**Photovoltaic**	**Concentrated Solar**
PC	$1.51	$4.62	$11.86	$48.12	$104.52	$363.19	$83.55
PC+CCS	-$391.63	-$367.50	-$311.21	-$29.17	$409.49	$2,421.23	$246.36
NGCC	$13.29	$19.95	$35.49	$113.34	$234.43	$789.74	$189.40
NGCC+CCS	-$365.92	-$308.85	-$175.68	$491.51	$1,529.20	$6,288.14	$1,143.29
IGCC	-$5.95	-$3.05	$3.72	$37.62	$90.36	$332.21	$70.75
IGCC+CCS	-$250.79	-$230.84	-$184.28	$48.99	$411.79	$2,075.63	$276.86

Carbon Price Intersections:

- Coal Price $1.60/MMbtu
- Natural Gas Price: $8.00/MMBtu
- Uranium Price: $0.50/MMBtu

Carbon Price Technology Indifference Points (COE1-COE2)/(Emissions2-Emissions1)/100					
	PC	PC+CCS	NGCC	NGCC+CCS	IGCC	IGCC+CCS
PC		$59.52	$47.96	$59.88	-$113.32	$47.96
PC+CCS	$59.52		$77.84	$64.03	$46.75	$422.77
NGCC	$47.96	$77.84		$75.35	$29.38	$47.96
NGCC+CCS	$59.88	$64.03	$75.35		$48.01	$159.42
IGCC	-$113.32	$46.75	$29.38	$48.01		$35.69
IGCC+CCS	$47.96	$422.77	$47.96	$159.42	$35.69	

	Nuclear	Hydroelectric	Geothermal	Wind (On-Shore)	Wind (Off-Shore)	Photovoltaic	Concentrated Solar
PC	$1.51	$4.62	$11.86	$48.12	$104.52	$363.19	$83.55
PC+CCS	-$391.63	-$367.50	-$311.21	-$29.17	$409.49	$2,421.23	$246.36
NGCC	-$51.75	-$45.09	-$29.55	$48.30	$169.39	$724.70	$124.36
NGCC+CCS	-$1,013.88	-$956.80	-$823.63	-$156.44	$881.25	$5,640.19	$495.34
IGCC	-$5.95	-$3.05	$3.72	$37.62	$90.36	$332.21	$70.75
IGCC+CCS	-$250.79	-$230.84	-$184.28	$48.99	$411.79	$2,075.63	$276.86

Carbon Price Intersections:

- Coal Price $2.00/MMbtu
- Natural Gas Price: $4.50/MMBtu
- Uranium Price: $0.50/MMBtu

Carbon Price Technology Indifference Points (COE1-COE2)/(Emissions2-Emissions1)/100						
	PC	**PC+CCS**	**NGCC**	**NGCC+CCS**	**IGCC**	**IGCC+CCS**
PC		$61.98	-$17.42	$17.74	-$110.79	$48.97
PC+CCS	$61.98		$187.74	-$501.60	$49.21	$470.58
NGCC	-$17.42	$187.74		$63.39	-$28.18	$163.24
NGCC+CCS	$17.74	-$501.60	$63.39		$8.93	-$243.10
IGCC	-$110.79	$49.21	-$28.18	$8.93		$36.81
IGCC+CCS	$48.97	$470.58	$163.24	-$243.10	$36.81	

	Nuclear	**Hydroelectric**	**Geothermal**	**Wind (On-Shore)**	**Wind (Off-Shore)**	**Photovoltaic**	**Concentrated Solar**
PC	-$3.11	-$0.01	$7.23	$43.49	$99.89	$358.56	$78.92
PC+CCS	-$444.25	-$420.12	-$363.82	-$81.78	$356.88	$2,368.62	$193.74
NGCC	$13.29	$19.95	$35.49	$113.34	$234.43	$789.74	$189.40
NGCC+CCS	-$365.92	-$308.85	-$175.68	$491.51	$1,529.20	$6,288.14	$1,143.29
IGCC	-$10.12	-$7.21	-$0.45	$33.46	$86.19	$328.04	$66.58
IGCC+CCS	-$286.04	-$266.08	-$219.52	$13.74	$376.54	$2,040.38	$241.62

Carbon Price Intersections:

- Coal Price $2.00/MMbtu
- Natural Gas Price: $8.00/MMBtu
- Uranium Price: $0.50/MMBtu

Carbon Price Technology Indifference Points (COE1-COE2)/(Emissions2-Emissions1)/100					
	PC	**PC+CCS**	**NGCC**	**NGCC+CCS**	**IGCC**	**IGCC+CCS**
PC		$61.98	$39.29	$54.98	-$110.79	$48.97
PC+CCS	$61.98		$97.90	-$27.11	$49.21	$470.58
NGCC	$39.29	$97.90		$75.35	$22.01	$65.62
NGCC+CCS	$54.98	-$27.11	$75.35		$43.63	$105.23
IGCC	-$110.79	$49.21	$22.01	$43.63		$36.81
IGCC+CCS	$48.97	$470.58	$65.62	$105.23	$36.81	

	Nuclear	**Hydroelectric**	**Geothermal**	**Wind (On-Shore)**	**Wind (Off-Shore)**	**Photovoltaic**	**Concentrated Solar**
PC	-$3.11	-$0.01	$7.23	$43.49	$99.89	$358.56	$78.92
PC+CCS	-$444.25	-$420.12	-$363.82	-$81.78	$356.88	$2,368.62	$193.74
NGCC	-$51.75	-$45.09	-$29.55	$48.30	$169.39	$724.70	$124.36
NGCC+CCS	-$1,013.88	-$956.80	-$823.63	-$156.44	$881.25	$5,640.19	$495.34
IGCC	-$10.12	-$7.21	-$0.45	$33.46	$86.19	$328.04	$66.58
IGCC+CCS	-$286.04	-$266.08	-$219.52	$13.74	$376.54	$2,040.38	$241.62

Carbon Price Intersections:

- Coal Price $1.60/MMbtu
- Natural Gas Price: $4.50/MMBtu
- Uranium Price: $0.50/MMBtu
- 25% Nuclear and Renewable Capital Cost Reduction

Carbon Price Technology Indifference Points (COE1-COE2)/(Emissions2-Emissions1)/100						
	PC	PC+CCS	NGCC	NGCC+CCS	IGCC	IGCC+CCS
PC		$59.52	-$8.76	$22.63	-$113.32	$47.96
PC+CCS	$59.52		$167.68	-$410.46	$46.75	$422.77
NGCC	-$8.76	$167.68		$63.39	-$20.80	$145.58
NGCC+CCS	$22.63	-$410.46	$63.39		$13.32	-$188.90
IGCC	-$113.32	$46.75	-$20.80	$13.32		$35.69
IGCC+CCS	$47.96	$422.77	$145.58	-$188.90	$35.69	

	Nuclear	Hydroelectric	Geothermal	Wind (On-Shore)	Wind (Off-Shore)	Photovoltaic	Concentrated Solar
PC	-$7.33	$4.62	$1.41	$25.60	$72.41	$260.23	$56.80
PC+CCS	-$460.44	-$367.50	-$392.44	-$204.35	$159.74	$1,620.48	$38.37
NGCC	-$5.70	$19.95	$13.07	$64.99	$165.49	$568.70	$131.99
NGCC+CCS	-$528.70	-$308.85	-$367.85	$77.11	$938.39	$4,393.88	$651.27
IGCC	-$14.22	-$3.05	-$6.05	$16.56	$60.33	$235.94	$45.74
IGCC+CCS	-$307.70	-$230.84	-$251.47	-$95.90	$205.23	$1,413.35	$104.84

Carbon Price Intersections:

- Coal Price $1.60/MMbtu
- Natural Gas Price: $8.00/MMBtu
- Uranium Price: $0.50/MMBtu
- 25% Nuclear and Renewable Capital Cost Reduction

Carbon Price Technology Indifference Points (COE1-COE2)/(Emissions2-Emissions1)/100						
	PC	**PC+CCS**	**NGCC**	**NGCC+CCS**	**IGCC**	**IGCC+CCS**
PC		$59.52	$47.96	$59.88	-$113.32	$47.96
PC+CCS	$59.52		$77.84	$64.03	$46.75	$422.77
NGCC	$47.96	$77.84		$75.35	$29.38	$47.96
NGCC+CCS	$59.88	$64.03	$75.35		$48.01	$159.42
IGCC	-$113.32	$46.75	$29.38	$48.01		$35.69
IGCC+CCS	$47.96	$422.77	$47.96	$159.42	$35.69	

	Nuclear	**Hydroelectric**	**Geothermal**	**Wind (On-Shore)**	**Wind (Off-Shore)**	**Photovoltaic**	**Concentrated Solar**
PC	-$7.33	$4.62	$1.41	$25.60	$72.41	$260.23	$56.80
PC+CCS	-$460.44	-$367.50	-$392.44	-$204.35	$159.74	$1,620.48	$38.37
NGCC	-$70.74	-$45.09	-$51.97	-$0.05	$100.45	$503.66	$66.95
NGCC+CCS	-$1,176.66	-$956.80	-$1,015.80	-$570.84	$290.44	$3,745.93	$3.32
IGCC	-$14.22	-$3.05	-$6.05	$16.56	$60.33	$235.94	$45.74
IGCC+CCS	-$307.70	-$230.84	-$251.47	-$95.90	$205.23	$1,413.35	$104.84

ELECTRICITY COST CALCULATIONS

Notes:

1. The mix of conventional electricity generation technologies is composed of pulverized coal (PC), Natural Gas Combined Cycle (NGCC), Nuclear, and Hydroelectric.

2. Absent a comprehensive policy establishing a carbon price, the current mix of generation technologies generate electricity between 4 to 5 cents/kWh.

3. Once a carbon price is established and it becomes increasingly costly to emit CO2, electricity generated from fossil fuels becomes increasingly expensive.

4. Although increased carbon prices make nuclear and hydroelectric generation more economically attractive, these technologies have other drawbacks. Hydroelectric is geographically dependent and nuclear waste and reprocessing are politically charge issues, especially in the United States.

5. Therefore, it is necessary to see how we can continue to use fossil fuels in a less carbon-intensive manner.

Cost of Electricity from Conventional Generation Technologies
Fuel Prices: Natural Gas=$4.50/MMBtu Coal=$1.60/MMBtu Uranium= $0.50/MMBtu

Y-axis: Cost of Electricity (cents/kWh)
X-axis: Carbon Price ($/Metric Ton of CO_2)

Legend: PC, NGCC, Nuclear, Hydroelectric
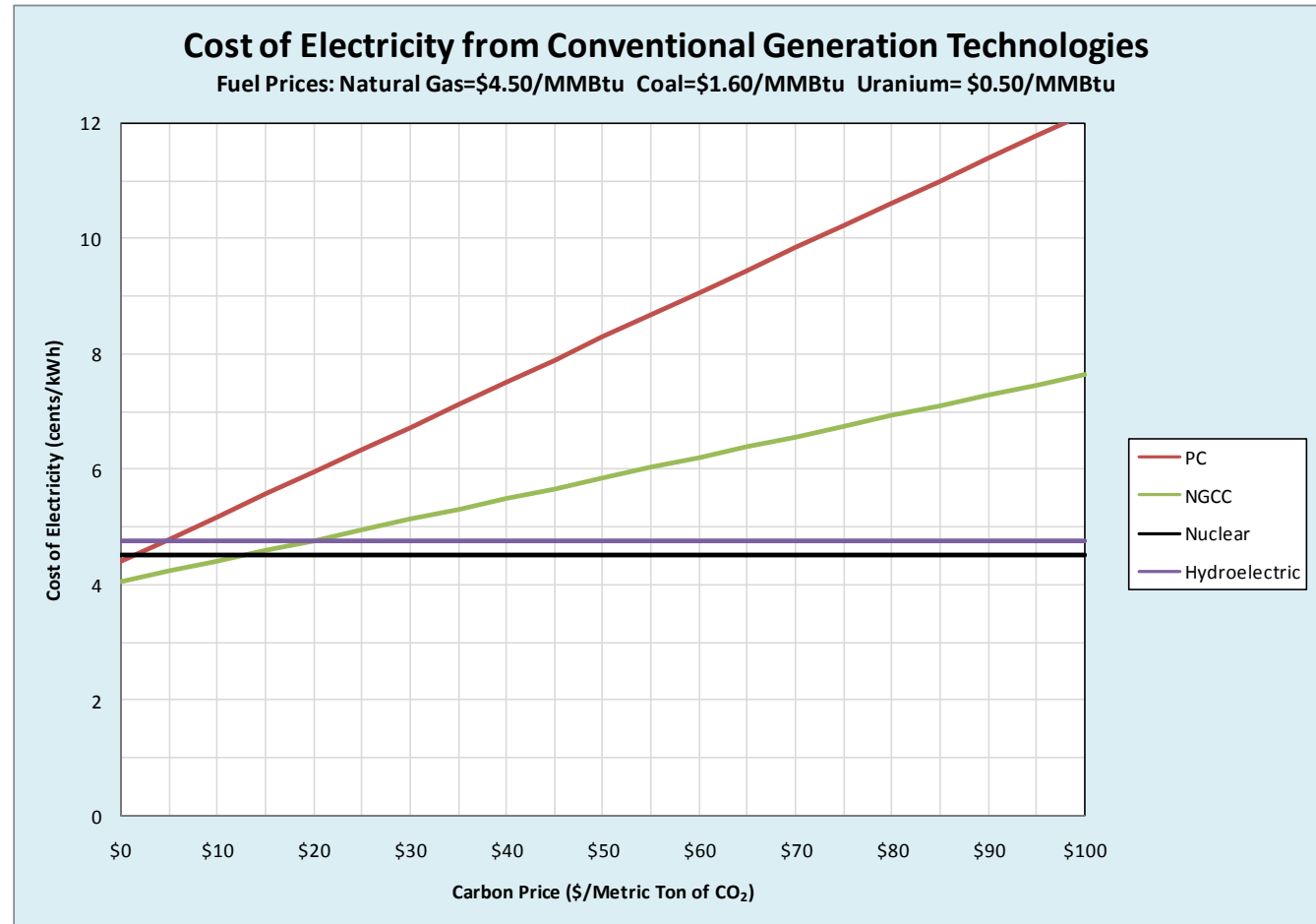
Carbon prices at intersection:
NGCC to NGCC+CCS: $63.39/metric
ton of CO2

Notes:

1. The primary abatement technology to reduce emissions from fossil fuel based electricity generators is carbon capture and sequestration (CCS). The dotted lines represent the cost of electricity generated at plants with CCS capacity.

2. The additional capital requirement for a CCS system includes components that capture CO2, compress the gas for transport, pipelines, and injection infrastructure.

3. It is important to note that we have added a new coal based generation technology: Integrated Gasification Combined Cycle (IGCC). This technology is currently available and more efficient than PC, but not widespread due to higher capital costs compared to conventional pulverized coal. However, it is less costly to capture carbon from an IGCC plant than a PC plant.

Cost of Electricity from Fossil Fuel Generation Technologies
Fuel Prices: Natural Gas=$4.50/MMBtu Coal=$1.60/MMBtu

4. Under reasonable fuel prices, we find that NGCC is generates the least cost electricity until the carbon price exceeds $63/Metric Ton of CO2, at which point NGCC+CCS becomes the least cost generation technology.

5. However, natural gas prices are volatile and have reached prices as high as $12/MMBtu in the United States during peak demand months in the recent past. At the same time, coal prices are historically stable.
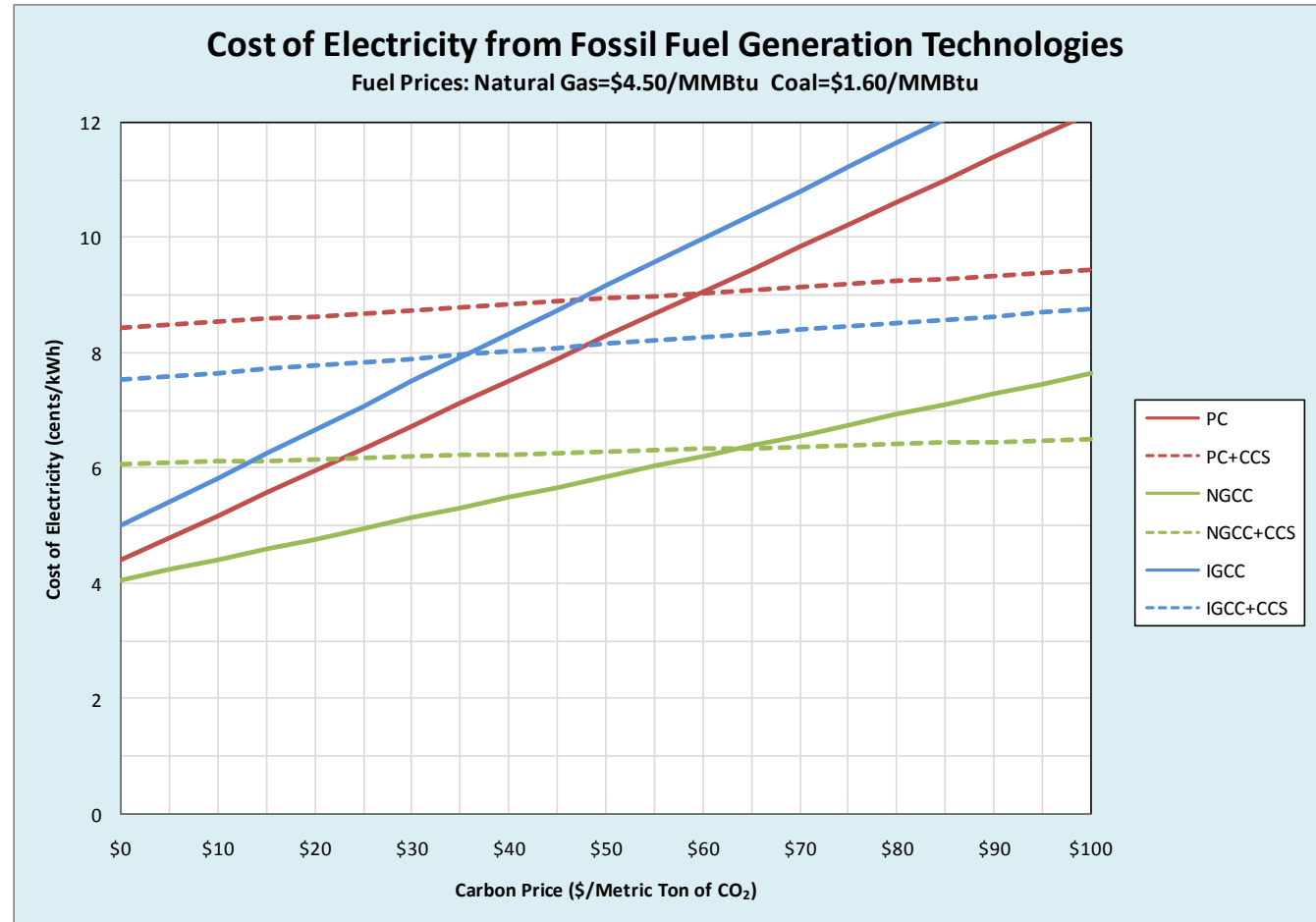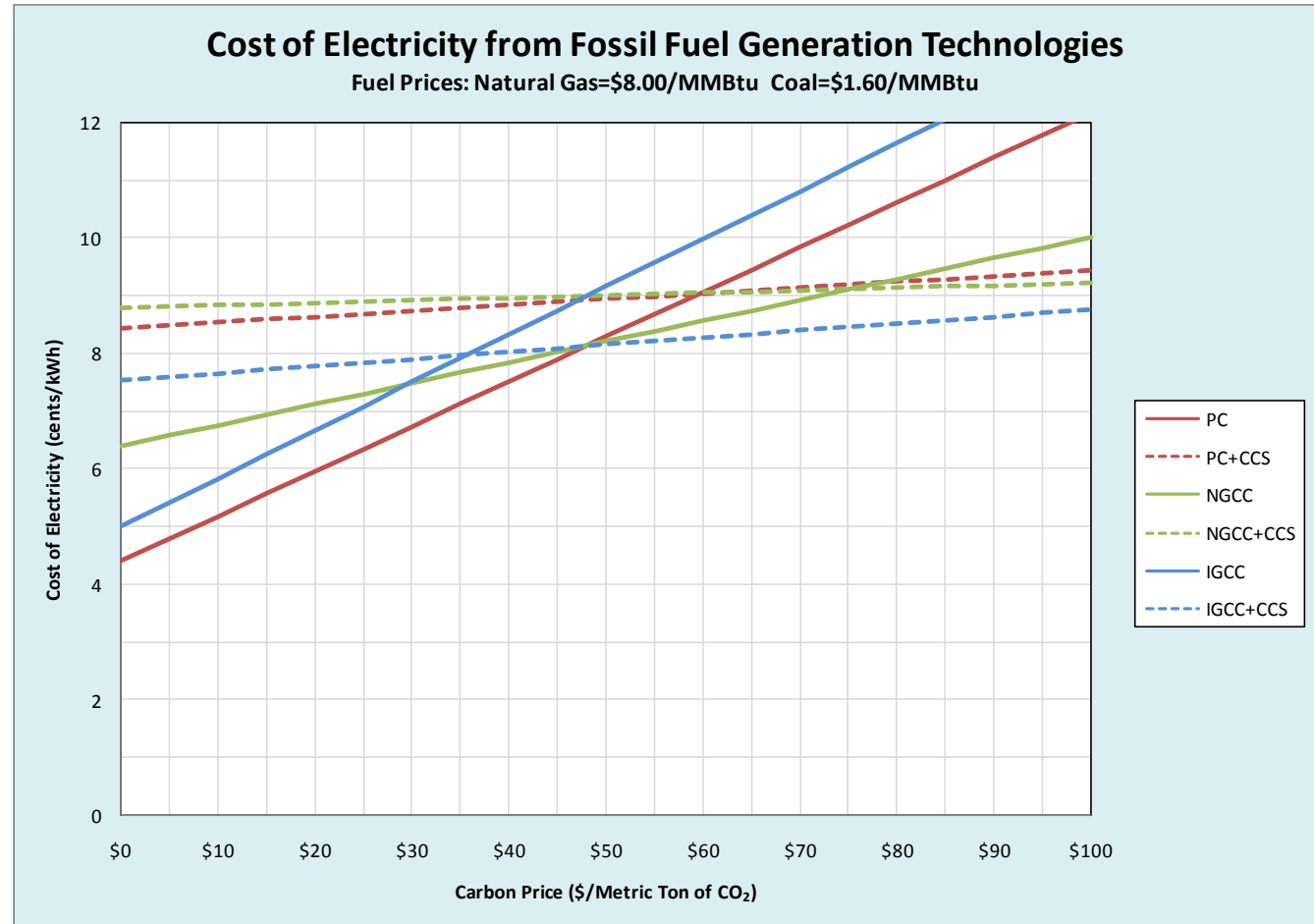
Carbon prices at least cost intersection:
PC to IGCC+CCS: $47.96/metric ton of CO_2
IGCC+CCS to NGCC+CCS: $159.42/Metric Ton of CO_2

Notes:

1. When we increase the price of natural gas to $8/MMBtu, we find that pulverized coal becomes the least cost generation technology up to a carbon price of just under $48/Metric Ton of CO_2, at which point IGCC+CCS becomes the least cost technology.

2. As the carbon price increases further, NGCC+CCS generates the least cost electricity at carbon prices higher than $159/Metric Ton of CO2.

3. It is important to point out that PC+CCS never generates electricity at a lower cost than IGCC+CCS under any reasonable carbon price. Therefore, we will not consider new PC+CCS as technologies likely to be implemented as carbon price increases.

Cost of Electricity from Fossil Fuel Generation Technologies
Fuel Prices: Natural Gas=$8.00/MMBtu Coal=$1.60/MMBtu

Carbon prices at notable intersection:
NGCC to Nuclear: $13.29/Metric Ton of CO_2
PC to Wind: $48.12/Metric Ton CO2

1. When we include non-fossil fuel-based generation technologies we find that, as stated earlier, nuclear and hydro provide the least cost electricity at higher carbon prices. However, hydro is geographically limited and nuclear waste disposal and reprocessing is politically sensitive, especially in the united States.

2. In this graph, nuclear becomes the least cost generation technology at a carbon price of $13.29/Metric Ton of CO2

3. Another important intersection to point out is where wind becomes less costly than PC and IGCC+CCS. At carbon prices higher than $48.12/Metric Ton of CO_2 wind generates electricity at a lower cost than IGCC.

Comparison of Renewable and Non-Renewable Generation
Fuel Prices: Natural Gas=$4.50/MMBtu Coal=$1.60/MMBtu Uranium= $0.50/MMBtu

4. Lastly, at a cost of roughly 24 cents/kWh, concentrated solar electricity generation does not even enter into the picture at any reasonable carbon price.

5. What is not captured in this comparison is the geographic dependence of the mentioned renewables which makes them less attractive than they appear in the absence of an expanded grid.
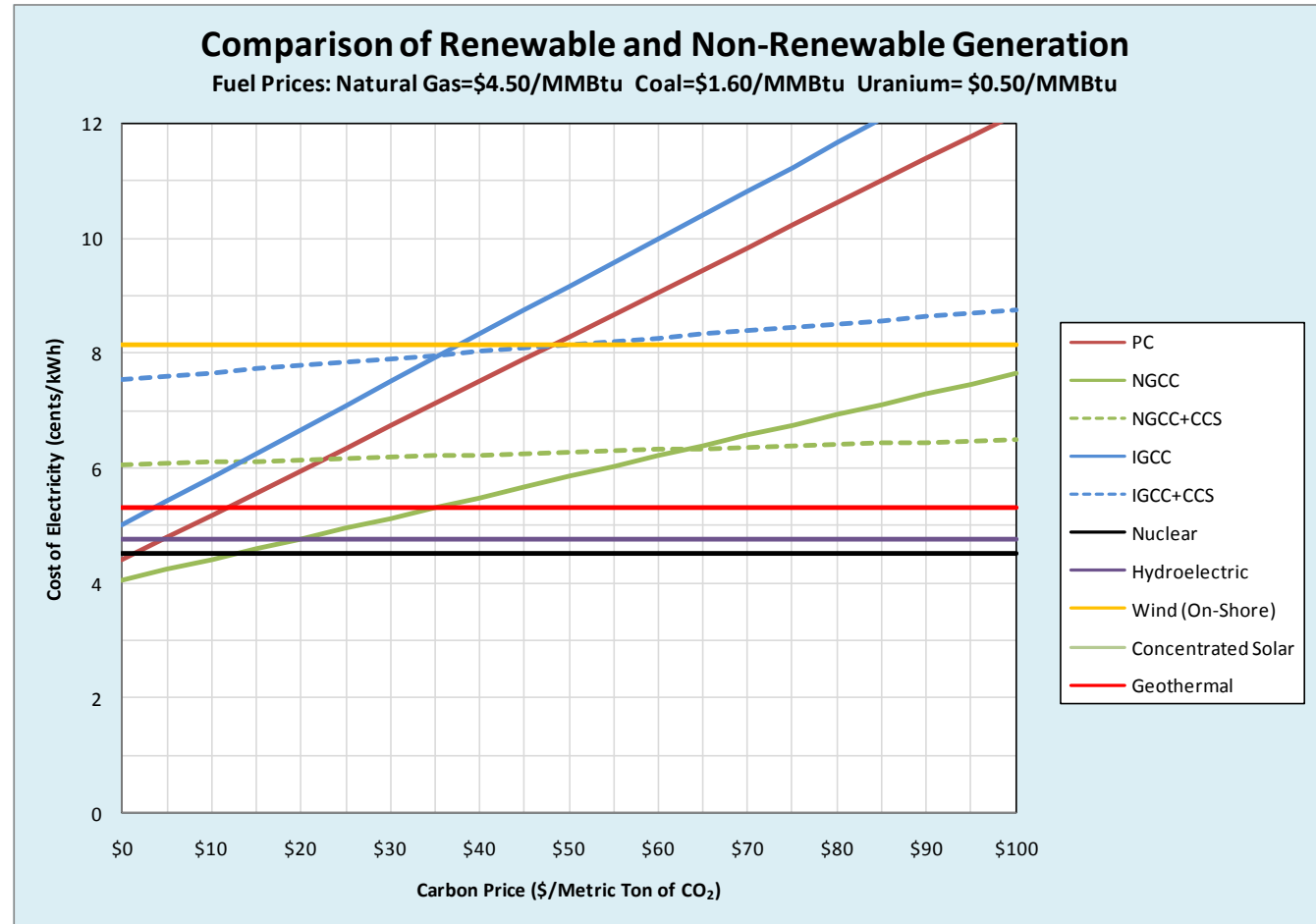
APPENDIX D

ELECTRICITY GENERATION FORECAST MODEL

Forecast Scenario to 2030

This project utilizes the Reference Case of the Energy Information Administration's (EIA) 2008 International Energy Outlook (IEO2008) to forecast OECD and Non-OECD generation mixes to the year 2030. To project consumption, EIA relies on the output of its World Energy Projections Plus (WEPS+) and System for the Analysis of Global Energy Markets/Global Electricity Module (SAGE/GEM) models that incorporate projected sectoral energy use, fossil fuel prices, and GDP growth among other factors for 16 regions of the world to 2030. A summary of the assumptions of these models is provided in Appendix J of the IEO2008, and full description of the models including analysis software is provided by request to EIA.

EIA provides raw data for each of its tables and figures of the IEO2008, and this project relies heavily on combined information from tables H8-H12. These tables contain EIA forecast information for net future generation from petroleum, natural gas, coal, nuclear, and renewable sources. Projections are provided for the world, OECD and Non-OECD countries, and select individual countries in billions of kilowatt hours. Importantly, EIA does not separate hydroelectric generation from other renewable sources. In order to more adequately assess the trajectory of non-hydro renewables, hydroelectric power had to be extracted from the estimates. To do this, hydro projections from the 2004 World Energy Outlook of the International Energy Agency (IEA) for 2005 and 2030 were subtracted from the figures provided by EIA. Because IEA did not provide full downloadable tables and only information for the first and last years of their forecast period, an annual rate of change was calculated manually for both hydro and non-hydro renewables.

 EIA projections were considered adequate until the year 2030 because its electricity forecasts have been quite accurate. The Annual Energy Outlook Retrospective compares forecasted values to observed values, and the average absolute percent differences for consumed quantities of electricity is not higher than four percent for any year. Further, EIA projections contain sophisticated analysis and include country-specific information unavailable in other forecasts. For example, EIA notes that Belgium and Germany plan to take several nuclear facilities off-line, and thus forecasts declining nuclear power in OECD Europe to the year 2030. However, EIA cannot be expected to perfectly predict the future, and has been critiqued for generally under-estimating consumption (Fischer, Herrnstadt, & Morgenstern, 2008; O'Neill & Desai, 2005). Despite these concerns, EIA projections were considered valid and used to forecast world generation mix through the year 2030.

Forecast Scenario 2030-2060

Few models project electricity consumption beyond 2030. Paul Kruger forecasts a 2.1-5.1 fold increase in consumption by the year 2050, but his methodology is not transparent (Kruger, 2004). Thus, we simply extended the growth of projected consumption from EIA figures to the year 2060. Under this assumption, total electricity consumption increases by 2.7 annually to approximately 65 trillion kilowatt hours. This figure is thus in the low-to-middle range of Kruger's projections.

Following the analysis described in Appendix A, the validity of EIA projections for electricity generation by fuel source was examined. For coal and petroleum, the growth patterns forecast by EIA seemed reasonable and thus the average annual rate of growth was simply extended thirty years following the equation $Consumption_t = Consumption_{2030}(1 + annual\ rate\ of\ growth)^t$. Thus, electricity generated from petroleum is expected to decrease globally over the next fifty years because the price of oil is projected to be sufficiently high as to preclude generation from petroleum. Additionally, since coal remains a cost-competitive source even under moderate carbon prices and faces no potential of depletion, the OECD and non-OECD rates of growth for coal were similarly extended through 2060. The annual growth rates of hydroelectric and non-hydro renewable were also extended, although these growth rates did not come directly from EIA as mentioned. Hydroelectric power continues declining over the fifty-year period because dam construction has been halted or reversed in many countries, and non-hydro renewables continue to grow at a slow pace due to the geographic dependencies of the sources.

For nuclear and natural gas, however, the EIA projections were considered adequate only to 2030. Our analysis demonstrates that nuclear power is the least-cost source under several scenarios. Therefore, the decline in OECD nuclear growth to 2030 is considered temporary, and the rate of OECD nuclear growth from 2030 to 2060 is increased from 0.6 to 1.6 percent. This increase is modest and reflects continued uncertainties about nuclear waste disposal and reprocessing, particularly in the United States. Additionally, our analysis shows that although natural gas can be very cost-competitive, its price volatility may hinder its further development. Under moderate carbon prices and at a high cost for fuel, natural gas production would be uneconomical and thus our forecast slows the rate of growth for natural gas from EIA's levels to 2030. From 2030-2060, natural gas slows from 2.6 percent to 2.0 percent annual growth in OECD. This decline is conservative and when combined with the expansion of nuclear production, preserves the total consumption projected from an extension of EIA's total global electricity forecast. It is important to note that our altered growth rates do not suggest the future for nuclear and natural gas is changed suddenly in 2030. It is simply projected that at some point, likely beyond that of EIA's forecast period, economic conditions of these fuel sources will drive alternate production decisions.

Electricity generation facilities are long-lived, and thus the supply forecast future contains great system inertia. The analysis of this project assumes a facility operating life of forty years, and thus decisions made about a new plant must consider the price of carbon not at the first day of production, but at a period decades into the plant's life. Due to this, the future mix of fuel sources in OECD and Non-OECD countries presented in this report largely represents the results of the most sophisticated models available, but also reflects the economic rationale of developers under assumed increasing prices of carbon dioxide.