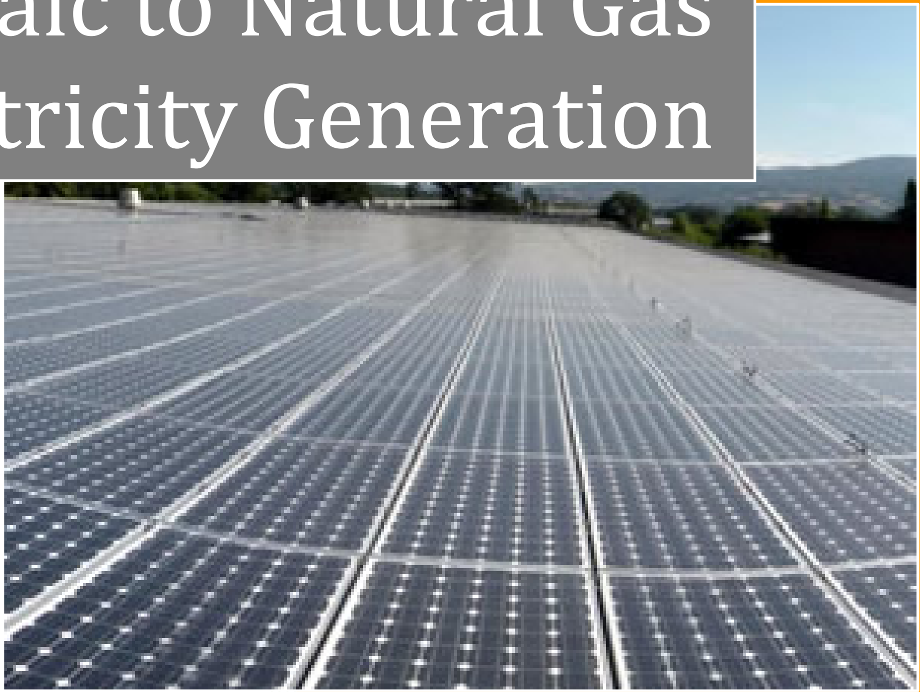
2010

Comparing Externalities of Solar Photovoltaic to Natural Gas Electricity Generation



Ancillary Impacts of Solar Photovoltaic Power

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State of Texas
Aimee Beveridge – Railroad Commission of Texas; Annie Carmichael – Vote Solar/SunEdison; Roberto Delgado, Mark Kapner and Leslie Libby – Austin Energy; Catherine Esparza – City of Austin, Brownfields; Cris Eugster – CPS Energy; Charlie Flynn and Bob Turnbull – CenterPoint Energy; Pam Groce – Texas State Energy Conservation Office; Theresa Gross, Richard Greffe & David Smithson – Public Utility Commission of Texas; Roslyn Kygar – Texas Commission for Environmental Quality; Lee Matecko – Whole Foods; Joel Mickey – ERCOT; Declan O'Cleirigh – Lower Colorado River Authority; Mica Odum – Meridian Solar; Karen Peycke – Environmental Protection Agency, Region 6; Lanny Sinkin – Solar San Antonio; Russel Smith – Texas Renewable Energy Industry Association; Soll Sussman – Texas General Land Office; Chirstine Whitney – Texas Commission for Environmental Quality

Key Acronyms and Abbreviations

BGD	Billion gallons per day
Btu	British thermal unit
CAIR	Clean Air Interstate Rule
CO_2	Carbon dioxide
CSP	Concentrating solar power
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
GHG	Greenhouse gas
GW	Gigawatts
JEDI	Job and Economic Development Impact Model
kW	Kilowatt
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
NETL	National Energy Technology Laboratory
NG	Natural gas
NGCC	Natural gas combined-cycle
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
PM	Particulate matter
ppb	parts per billion
ppm	parts per million
PV	Photovoltaic
SO_2	Sulfur dioxide
VOC	Volatile organic compounds

Executive Summary

The U.S. economy is heavily dependent on nonrenewable fossil fuels for its electricity. It is widely known that the supply of these nonrenewable resources is large yet limited. Renewable sources of electricity are currently needed to meet incremental demand in the short term and will play an increasingly important role as the United States continues to create an infrastructure that does not rely exclusively on fossil fuels. Solar photovoltaic (PV) provides the ability to generate clean energy while using existing electrical transmission infrastructure, or even bypassing it entirely. In order to gain a more robust understanding of the implications of electricity generation, this study compares PV solar power to conventional fossil fuel generated electricity – primarily natural gas – with respect to five ancillary impacts beyond energy generated and cost of generation.

Solar PV has an advantage over other renewable technologies because it can be deployed at a small or a large scale, making distributed generation and utility-scale installations equally feasible. In addition, the ubiquity of sunlight makes solar PV feasible in regions and sites with varying degrees of sunlight exposure.

The purpose of this study is to examine ancillary impacts of solar PV relative to natural gas that are relevant to many stakeholders. After speaking with industry experts and leaders at various levels of government, the following five ancillary impacts emerged as the most significant, quantifiable, and relevant:

- Water use
- CO_2 emissions
- NO_X emissions
- Health benefits of avoided emissions
- Job creation and economic benefits to a community or region

The ancillary impacts are important in examining electrical generation capacity additions at a community or regional level in order to gain a more holistic understanding of solar PV. This study uses a natural gas combined-cycle (NGCC) as a baseline for comparison with photovoltaic solar energy throughout its analysis. The production profile of PV follows peaking natural gas generation; PV thus competes most directly with peaking natural gas plants. Additionally, solar PV and gas-fired peaking plants are also the closest competitors on a cost per-kilowatt hour basis.

Water Use

Water and energy are inextricably linked, particularly in the electric power sector. Thermoelectric power plants withdraw a significant amount of water compared to solar PV projects and thus depend on reliable access to freshwater. Over the past decade, water resource constraints have even prevented the construction of several power plants, particularly in the southwestern U.S.

Several energy research institutes have attempted to predict water resource availability and to pair these predictions with energy demand projections. These studies indicate that an increasing number of electric utilities in the U.S. will be affected by water scarcity. Certain renewable technologies, such as solar PV, withdraw and consume significantly less water than thermoelectric power plants and can help to alleviate the electric power sector's dependency on this scarce and valuable resource.

CO_2 Emissions

The concentration of carbon dioxide (CO_2), a greenhouse gas, in the Earth's atmosphere has increased significantly over the past century. Greenhouse gases (GHGs) trap solar radiation, which increases surface temperatures on Earth. This phenomenon, known as global climate change, is projected to create many problems across the globe including: an increase in global sea level, an increase in severe weather events, and loss of valuable biodiversity, among others.

A NGCC plant burns natural gas in order to generate electricity and therefore emits more CO_2 per megawatt hour (MWh) than a solar PV plant, which converts sunlight directly into electricity without the use of fossil fuels. In addition to reducing environmental impacts, the emissions avoided by generating electricity using solar PV (compared to NGCC) can be expressed in economic terms in the states or regions where a CO_2 emissions market exists. Generating electricity using a 3 megawatt (MW) PV solar installation instead of a NGCC plant, for example, will avoid approximately 2,540 short tons of CO_2 emissions annually. These savings can be translated into monetary savings, depending on the price of CO_2. A 3 MW solar PV project would save $28,375 annually at a price of $10 per ton of CO_2 and $170,250 at a price of $60 per ton of CO_2.

NO_X Emissions

NO_X, nitrogen oxides, are produced during combustion of nitrogen rich fuels (e.g., fossil fuels) at high temperatures. NO_X compounds are air pollutants in their own right, but nitrogen also reacts with oxygen in the atmosphere to form ozone (O_3), which creates smog at the Earth's surface. Additionally, NO_X compounds react with water to produce nitric acid, a major component of acid rain. Prevention of NO_X emissions is thus critical to the prevention of smog and acid rain.

Under the Clean Air Act, power generating facilities are required to monitor and control NO_X emissions. The U.S. Environmental Protection Agency (EPA) regulates NO_X emissions from electric generating sources through a cap and trade program and has administered three successive NO_X trading schemes since the passage of the Clean Air Act Amendments of 1990. Since a PV power plant does not emit NO_X, this study assumes that the direct economic benefit of a PV plant compared with a natural gas plant can be quantified as the total cost of NO_X emissions per year. A 5 MW solar plant, for example, will save $5,368 per year at a price of $800 per ton of NO_X. These costs represent the money that would be spent on NO_X allowances on the open market.

Health Benefits of Avoided Emissions

Because solar PV emits negligible amounts of pollutants throughout the lifecycle of the plant, PV offers a significant public health benefit over fossil fuel generation, including natural gas-generated power. Gas-fired power accounts for 10 percent of national anthropogenic NO_X emissions.

NO_X reacts with water and sunlight to form dangerous concentrations of ground-level ozone (O_3) in the summer. Elevated concentrations of ozone create smog and irritate human lungs, leading to respiratory inflammation, particularly for children, the elderly, athletes who frequently exercise outdoors, and individuals with asthma. NO_X also reacts with ammonia, moisture, and other particles in the atmosphere to form particulate matter in the form of nitrates. Exposure to high concentrations of fine particles can cause new cases of chronic bronchitis, decreased lung function in children and asthmatics, and aggravation of respiratory or cardiovascular illness in children and individuals with heart or lung disease.

The health problems caused by ground-level ozone and fine particulate matter impose significant costs in the form of increased hospital visits, lost wages, and in the case of particulate matter, premature death. EPA estimates that reducing power plant emissions of SO_X and NO_X under its proposed Transport Rule would save between 14,000 and 16,000 lives and yield $120 to $290 billion in health and welfare benefits. PV electricity generation reduces the instances of these adverse health impacts through avoidance of NO_X and GHG emissions.

Job Creation and Economic Benefits

Solar PV development provides economic benefits to the communities and regions that host solar installations. PV projects create jobs and increase economic activity and tax revenues for local and state governments. Studies from the University of California Berkeley, the California Public Interest Research Group (CALPIRG) and BBC Research and Consulting support the claim that developing solar energy resources will result in net job creation.

The estimates for job creation provided by these groups vary widely. Solar PV creates 7.1 to 35.5 construction and installation jobs and 0.12 to 1 operations and maintenance (O&M) job per MW. By contrast natural gas plants create approximately 1 construction and installation job and 0.13 O&M jobs per MW. This variability in job estimates highlights the importance of examining the assumptions and models used in any study estimating job creation before comparing one study to another.

The Job and Economic Development Impact Model (JEDI) is the best tool available to evaluate the economic impact of solar development projects for a specific state or region. The JEDI model provides an estimate of the total direct, indirect, and induced jobs created from a particular project, and an estimate of the earnings and total economic output from these jobs and of the tax revenue generated as a result of the project. JEDI models can also compare job creation and economic impacts between different generation sources and projects.

Conclusion

These five key ancillary impacts of solar are particularly relevant to the individuals and institutions that set policies and may encourage or hinder the development of certain electricity sources, stakeholders near project sites, and electricity consumers. As demonstrated in three case studies at the end of this report, the magnitude and relevance of each impact depends on the project's size and geographic location. Regardless of the magnitude of the ancillary impacts from PV development, it is critical to examine PV and other electricity generation projects on a more holistic level to fully understand and account for all their impacts – economic and ancillary impacts alike.

Introduction

Although solar power is not cost-competitive with conventional electricity generation in most markets, it can provide important benefits to society that may not be captured in a developer's or regulator's financial analysis of a project. This report proposes a broader approach to comparing solar PV power to its most common competitor, natural gas, by considering five impacts that are important to developers, regulators, and community leaders and are relevant at the project level: water use, cost and environmental impacts of avoided NO_X emissions, human health impacts of avoided NO_X emissions, avoided CO_2 emissions, and job creation. The purpose of this study is to provide the University of Michigan, state and regional planners, and the broader solar community with a reference tool to develop a high-level but comprehensive understanding of these impacts of solar PV generation.

The report begins by outlining its key assumptions and scope limitations. It then discusses each of the five ancillary impacts and outlines existing research that addresses the relative impact of solar to natural gas. Finally, it includes three case studies of projects and examines the relative strength of the ancillary impacts applied to these cases.

Why Focus on Solar?

This study compares solar PV power to conventional fossil fuel generated electricity. The authors believe that solar is an interesting case study for many reasons. First, the U.S. economy is heavily dependent on nonrenewable fossil fuels for its electricity, and the supply of these resources is large but limited. In 2009, the United States relied on non-renewable fossil fuels for 69 percent of its electricity (U.S. EIA, 2010c). The U.S. Energy Information Administration (EIA) projects that electricity demand will increase by 30 percent between 2008 and 2035, which will deplete nonrenewable sources at a faster rate (U.S. EIA, 2010a). Thus, renewable sources of electricity like solar PV are needed to fill some demand growth in the short term and create a new electricity generation infrastructure that does not depend on fossil fuels in the long term.

Second, solar power generates benefits that are not reflected in traditional financial analyses of power development projects. Community benefits such as decreased pollution and job creation are relevant to local, state, and regional planners but not necessarily to investor-owned utilities examining proposals to fill supply needs. For this reason, a gap exists between the actual benefits provided by solar power and a project's cost per kilowatt-hour of generation that this study could address.

Third, solar PV has an advantage over other renewable technologies because it can be deployed at small or large scale, making either distributed generation or utility-scale installations possible. Solar PV can be deployed through a few panels installed on a residential rooftop or a football field-sized solar PV farm. This feature enables solar, unlike other renewable technologies like biomass or most wind generation, to bypass existing transmission infrastructure if necessary and generate electricity close to load centers.

Fourth, the ubiquity of sunlight as an energy source makes it attractive almost anywhere. Solar insolation may be strongest in the southwestern U.S., but solar electricity is feasible in most regions of the U.S. Germany has approximately the same solar resource as the Pacific Northwest in the U.S., yet it has become the global leader in solar electricity generation (NREL, 2008). Although solar resources in the U.S. are much stronger, Germany's installed solar capacity exceeds the U.S. capacity by 8,000 MW (SEIA, 2010).

Project Scope

This study focuses on PV solar as opposed to other forms of solar generation such as concentrating solar power (CSP) for a few reasons:

First, solar PV is a proven technology. PV cells were first developed in 1954, and satellites have used solar PV technology for power since the early 1960's (U.S. DOE, 2005). Although panel and systems technologies continue to improve, the basic concept of solar PV has a long track record of successful deployment.

Second, solar PV can produce power in regions and sites with varying degree of sunlight exposure, also known as insolation. Other solar technologies such as CSP require very high direct sunlight that is only available in certain parts of the world.

Third, solar PV is scalable. It can be deployed through an object as small as a backpack or a modular installation as large as several square miles. This study focuses on wholesale utility scale PV generation, but its findings could be applied to larger or smaller installations.

This study compares solar PV installations to NGCC power plants. A NGCC plant uses both gas turbines and steam turbines to generate electricity. The plant burns and pressurizes natural gas and uses the resulting energy to drive a turbine-generator. Heat recovery steam generators capture the waste heat from the gas turbine and use it to generate additional electricity, increasing the efficiency of the plant (EPRI, 2002).

This study uses a natural gas combined-cycle power plant as the baseline for comparison with photovoltaic solar energy throughout our analysis for two main reasons:

First, solar PV competes directly with peaking natural gas plants. The PV production profile naturally follows peak electricity demand; when demand is highest during the height of the afternoon, PV is producing at its highest levels. Natural gas plants can be easily started and stopped, and thus are also used to fulfill peak power demand. Demand that is not met by PV generated electricity would most likely be met by a NGCC peaking plant (U.S. EIA, 2010a). Because coal-fired power is used to meet baseload rather than peaking generation needs, a comparison of solar PV to coal would be relevant to fewer markets than the comparison to natural gas.

Solar PV is also most comparable to gas-fired peaking plants on a per-kilowatt (kW) cost basis. This is primarily due to low capacity factors of these generating stations, which typically operate less than 10 percent of the day (WI PSC, 2009). Thus, the cost of building the plant is allocated over fewer MWh of electricity, leading to higher generated electricity costs.

Second, natural gas generation is growing and will remain an important source of electricity in the U.S. under many possible regulatory scenarios. Natural gas is projected to provide 21 percent of the United States' electricity demands by 2035, and more than 50 percent of all new planned capacity in the U.S. for 2010 to 2013 will be met with natural gas plants (U.S. EIA, 2010a). Large, recent discoveries of gas reserves in the United States, particularly in the Marcellus Shale region, have promised plentiful domestic supply for the foreseeable future. Natural gas-fired plants also emit half the amount of GHGs as coal-fired plants and are expected to remain an important source of electricity whether or not the U.S. government regulates GHG emissions. For a discussion on the price volatility of natural gas, refer to Appendix C.

Rationale for choice of five metrics

As previously discussed, the purpose of this study is to examine ancillary impacts of solar PV relative to natural gas that are relevant to planners thinking at a community or regional level. To determine which impacts to discuss, the team examined three state electricity markets for solar development potential and used industry studies, academic studies, interviews with policymakers, meetings with state and local government officials, and discussions with utilities and other industry experts to explore potential impacts of solar PV development. This research yielded five factors that are significant, quantifiable, and relevant to stakeholders. They are: water usage, CO_2 emissions, NO_X emissions, public health impacts of avoided emissions, and job creation and economic impacts to a community or region.

Water Use: Water and energy are inextricably linked, particularly in the electric power sector. Fuel extraction and electricity generation both require a significant amount of water, and water pumping, treatment, and transport require energy. As the population of the U.S. continues to grow and fresh water sources become increasingly scarce, the electric power sector will compete directly with agriculture and drinking water for water resources. Solar PV electricity requires very little water and can help to alleviate the pressure on fresh water sources.

CO_2: CO_2 is considered a GHG due to its ability to retain heat and water vapor in the Earth's atmosphere, and is essential to respiration, the process by which plants produce oxygen. Fossil fuel and biomass power generation emit significant amounts of GHGs into the atmosphere. As policymakers have considered whether and how to regulate greenhouse gas emissions, developers and state rate-setting agencies have worried about uncertainty in the future costs of operating fossil fueled power plants. This study discusses some of the differences between PV generated electricity and natural gas generated electricity in terms of CO_2 emissions and studies the implications in monetary terms if a price on CO_2 were adopted in the U.S.

NO_X Emissions: NO_X are produced during combustion of nitrogen rich fuels (e.g., fossil fuels) at high temperatures. Under the Clean Air Act, power generating facilities are required to monitor and control NO_X emissions, as these emissions pose significant environmental and health risks. NO_X compounds are air pollutants in their own right but nitrogen also reacts with oxygen in the atmosphere to form ozone, which creates smog at the Earth's surface. NO_X compounds also react with water to produce nitric acid, a major component of acid rain. This study focuses on these impacts as well as the cost uncertainty of future NO_X permits.

Health Impacts: NO_X emissions from power plants react with atmospheric particles to form ozone and fine particulate matter, which can aggravate existing respiratory health problems and contribute to increased hospital visits and health care costs and premature death. This study outlines the conclusions of major epidemiological studies of the health impacts of increased ozone and particulate matter concentrations in ambient air and describes modeling used to estimate health impacts of emissions.

Local and Regional Job Creation: Given the current economic and political climate in the United States, solar industry experts and stakeholders alike are interested in the impact that solar development can have on the local and national job markets and community economic development. Multiple studies indicate that the broader economic impact of PV development is not captured in project economics. This study examines a model developed by the National Renewable Energy Laboratory (NREL) to capture these impacts, which includes the impacts on jobs in conventional generation from increased development of solar generation. It also discusses the types of jobs created by solar development and the job creation impact of investments in solar PV and conventional sources of electricity.

This study acknowledges that its research exploring all ancillary impacts is not exhaustive. The sources used to identify these impacts were limited in geography and time period, and similar research in different geographies, regulatory landscapes, and times could yield a different set of relevant impacts. See Appendix A for a list of all metrics considered for this analysis.

While the focus of this study is ancillary impacts, it is important to also acknowledge the risks and drawbacks associated with the widespread adoption of solar power generation.

Cost

Energy costs vary widely and depend on demand, time of day, fuel generation mix, fuel costs, and transmission capacity, among other factors. Traditional baseload generation uses coal, natural gas, or nuclear materials as fuel sources and is typically less expensive per kW of production. While actual costs vary widely across technologies and geographies, the EIA estimates the economic cost of constructing a 5 MW PV system (prior to investment tax credits) to be approximately $5,880 per kW. By comparison, for a new 600 MW scrubbed coal plant costs about $2,080 per kW and a new 1,350 MW advanced nuclear facility costs $3,310 per kW (U.S. EIA, 2010b). Utility customers generally bear these extra costs in the form of higher rates, which draws criticism from ratepayers and consumer advocacy groups.

In addition to the relatively high overall cost of PV systems, financing solar PV projects can be difficult because most costs are incurred prior to any revenue generation. The costs are almost exclusively capital outlays, and the amount and timing of future cash flows from selling power are uncertain. PV systems do not require fuel—a significant expense for thermoelectric power plants—and require minimal operations and maintenance expenses such as bi-annual PV panel washing. As described in the section below, solar insolation is irregular and unpredictable. Although developers can accurately project output from a PV system over its lifetime, the precise amount of power and timing of its production—and therefore incoming cash flows—are difficult to predict. This means that a project developer must secure financing for construction without an absolute guarantee of future cash flows from the sale of electricity generated by the PV panels.

Intermittency/Reliability

Solar insolation can be intermittent and unreliable. PV panels can only produce electricity during daylight hours; they do not generate electricity after the sun has set. Even if the sun is shining, passing clouds or shade from nearby buildings or trees can interrupt electricity production from the PV panel. Dust can also accumulate on the panel, reducing its efficiency and decreasing the energy output. The unpredictable nature of solar energy production can reduce reliability of the electrical grid in any area. Incorporating energy storage into the design of a solar facility can smooth out the facility's output to the electrical grid, but storage adds costs to an already expensive generating facility.

Land Use Requirements

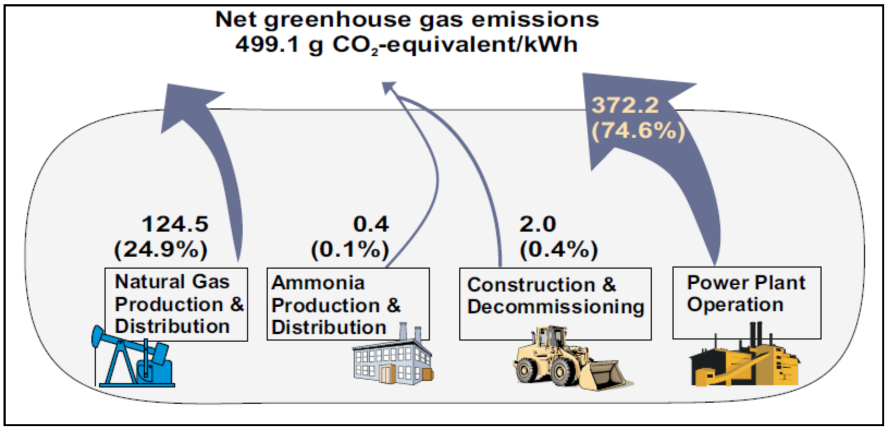
PV systems require more land than traditional thermoelectric power plants. PV panels cannot be placed on top of one another and must maintain a certain distance from adjacent panels to avoid shading. In addition to the land needed for the panels, the outside border of the array must include a buffer for wiring and transmission. While land use requirements vary widely depending on the geography, insolation, and technology used, industry experts typically assume that 1 MW of PV capacity will require 7 acres of land. This translates to 0.14 MW energy output per acre. Traditional sources of electricity have much more dense energy output per acre. A proposed 1500 MW coal plant in Surry County, Virginia, for example, will be built on 1600 acres, generating approximately 0.94 MW energy output per acre (McNatt, 2010). Using land for a solar PV installation also prevents alternative uses such as agricultural production or ecosystem services, which could be very important for certain regions and sites.

Boundaries of Impact Analyses

The study limits the value chain within which impacts of gas-fired plants and solar PV installations occur based on the impact intensity of each part of a project's life cycle and the accuracy of impact estimates. Given where the impact occurs in each source's life cycle, this study uses different parts of each life cycle for each source.

The majority of all impacts generated over the life cycle of a natural gas-fired power plant can be attributed to fuel combustion during plant operation. In 2000, the NREL estimated that 99.5 percent of all emissions during the lifetime of a combined-cycle plant – defined from the start of plant construction to its retirement, including natural resource (fuel) extraction in its use phase – result from fuel combustion during power plant operations (NREL, 2000). Because the same activities that create CO_2 emissions generate NO_X emissions and use water, this study assumes that this energy-intensive stage of the plant's life also includes the same proportion of NO_X release and water use as CO_2 emissions. Figure 1 below depicts the overall total greenhouse gas emissions (in g CO_2e) over the lifetime of a natural gas power plant.

Figure 1. GHG Emissions over Lifetime of a Natural Gas Power Plant



(NREL, 2000)

By contrast, the majority of impacts generated over the life cycle of a solar PV panel can be attributed to the manufacturing phase. Once installed, energy derived from PV does not require any resource inputs or generate any airborne emissions or waste materials. In effect, the overall impact is contributed at the beginning the project's life cycle.

Due to these inherent differences between natural gas and PV generation, the project boundaries in the study vary when comparing the impacts of a combined-cycle natural gas power plant with an equivalent capacity PV plant. The analysis of natural gas plants includes all impacts that occur once the plant is connected to the grid (i.e. operational and generating electricity). In addition to encompassing roughly 98 percent of the total impacts associated with the power plant, this segment is fairly consistent across natural gas plants of similar nameplate capacity. For example, two similar 200 MW natural gas plants with similar roles in providing power to the grid will have very comparable fuel requirements and resulting impacts, whereas the upfront energy requirements in the construction phase could vary. For PV, upstream activities are included within the impact estimate boundaries because they encompass the vast majority of all impacts associated with PV electricity occurring during the manufacturing stage.

Figures 2 and 3 below depict the boundaries for the PV system and natural gas plant discussed in this study. It is important to note that while the boundaries capture different phases in the lifetime of the two energy sources in this discussion, they encompass the most impactful and energy intensive activities for each generation source.

Figure 2. PV Project Boundaries for this Analysis[1]

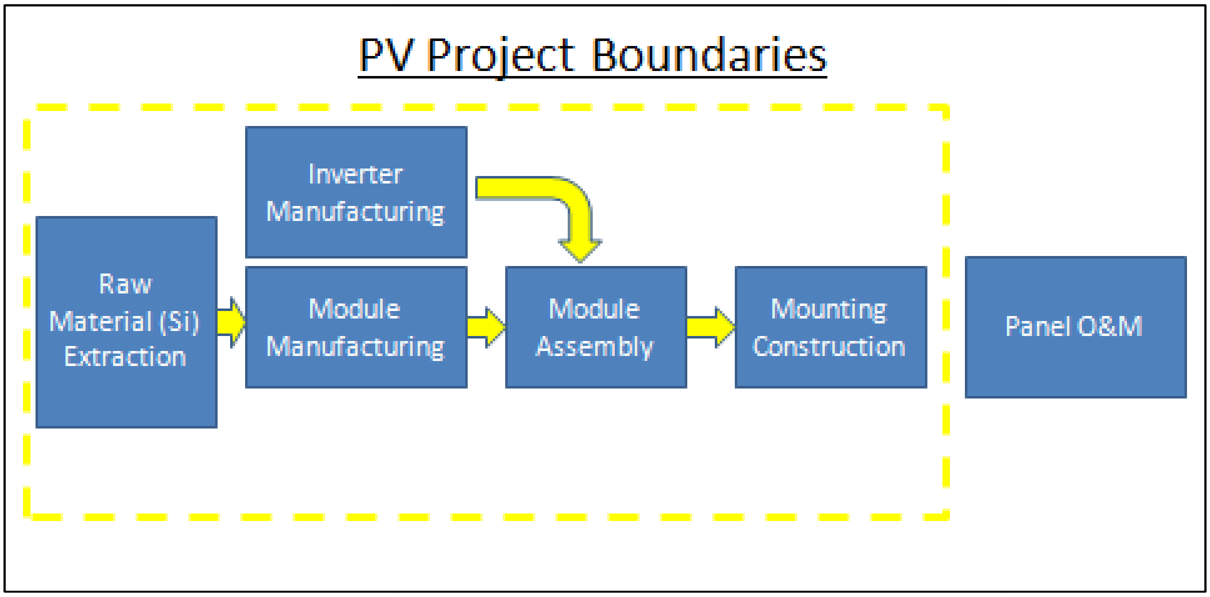
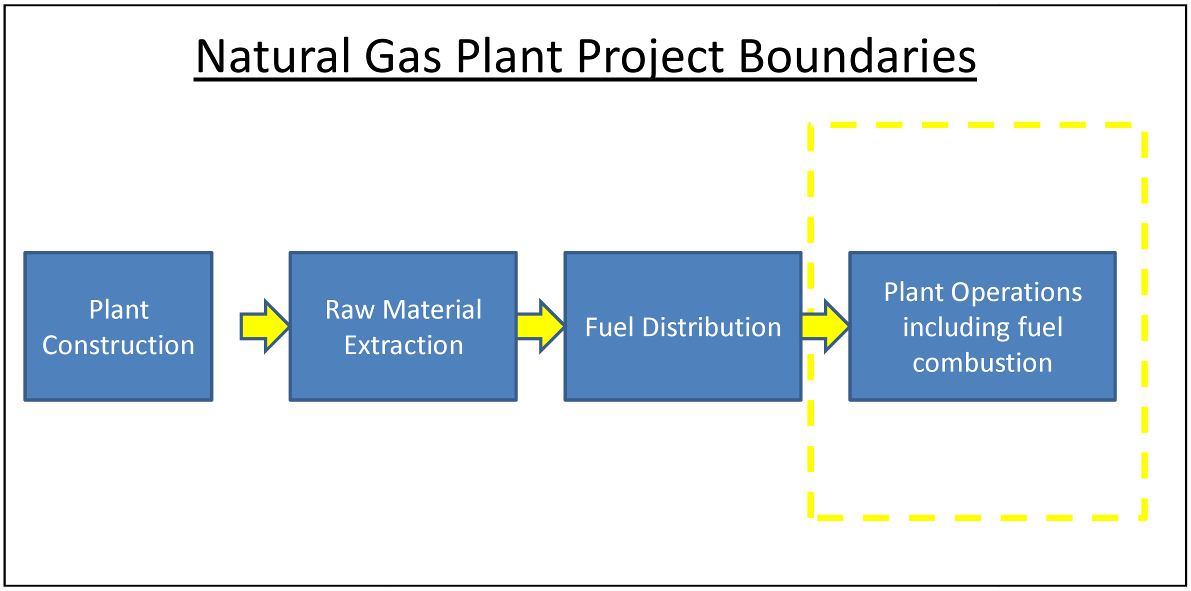


Figure 3. Natural Gas Plant Project Boundaries for this Analysis[2]



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[1] All raw material extraction occurs once during the initial manufacturing stage.

[2] All raw material extraction occurs throughout the lifetime of the plant as fuel is continuously delivered for the plant operations.

Chapter 1: Water Use

Water and energy are inextricably linked, particularly in the electric power sector. Water pumping, treatment, and transport require energy; fuel production and electricity generation require water. Population growth and the rising number of incidents of drought challenge the sustainability of the nation's water resources.

Water resources also play an important role in the power plant siting process, particularly in areas prone to drought. In 2002, for example, the Idaho Department of Natural Resources (IDNR) denied two applications for water rights permits for two proposed natural-gas-fired power plants, which would withdraw cooling water from a local aquifer. IDNR concluded that the proposed water uses were not consistent with the conservation of water resources in Idaho (Associated Press, 2002) (Rocky Mountain Mineral Law Foundation, 2002). In addition, the Idaho House of Representatives unanimously approved a two-year moratorium on the construction of coal-fired power plants, finding that such plants may have a significant negative impact upon "the environmental quality and natural resources of the state of Idaho," among others (Idaho Code, 2006).

This chapter examines the water use factors of thermoelectric power cycles and of renewable energy technologies and summarizes current projections for water needs over several future energy generation scenarios.

Current Water Use in U.S. Electricity Generation

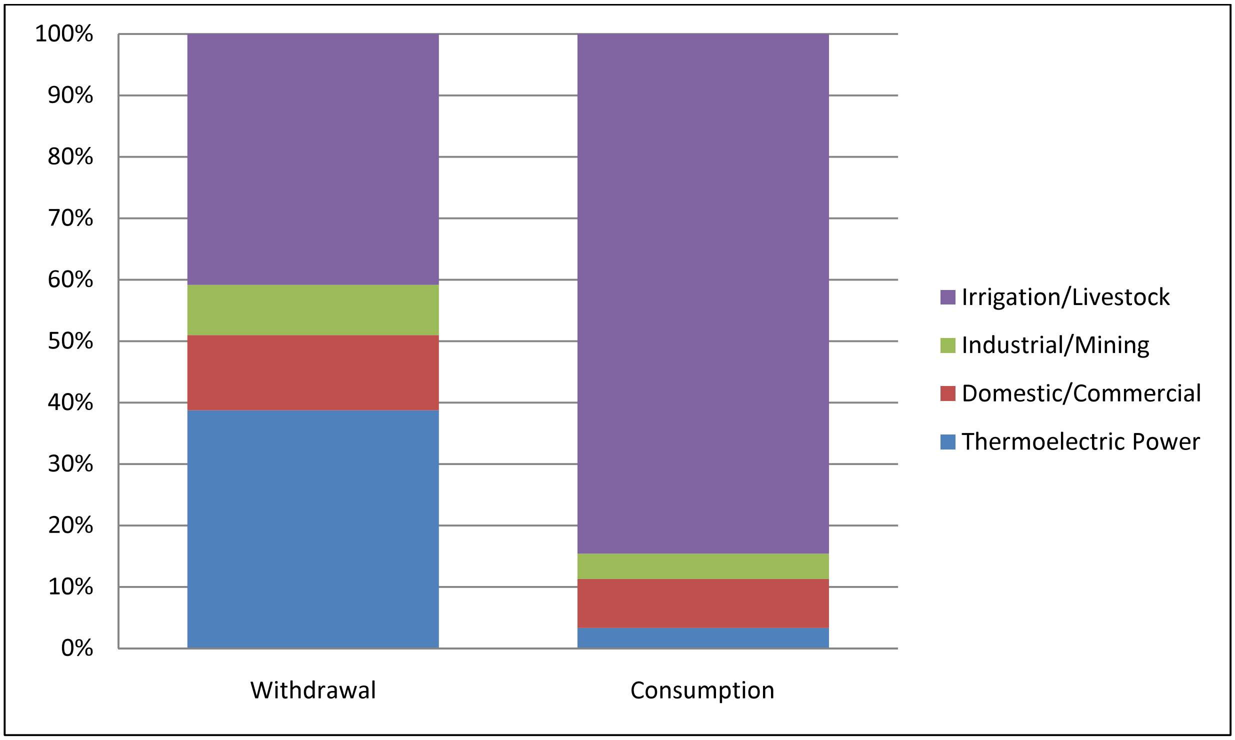
When describing and quantifying water use in the electric power sector, it is important to distinguish between water withdrawal and water consumption. The U.S. Geological Survey (USGS) defines a water withdrawal as water removed from a ground or surface water source for use. USGS uses water consumption to refer to, "that part of water withdrawn that is evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (USGS, 2010).

The sections below describe the amount of water currently withdrawn and consumed for electric power generation in the U.S. both for a combined cycle natural gas power plant and a utility-scale photovoltaic installation. See Appendix B for a comparison across all traditional, thermoelectric power plant types (coal, natural gas, nuclear) and across renewable energy technologies.

Thermoelectric Power Plants

Thermoelectric power plants withdrew 49 percent of the total water withdrawn in the U.S. in 2005, approximately 201 billion gallons per day (BGD) (USGS, 2009). But, the total water consumed by thermoelectric power plants is much lower than the total water withdrawn. In 1995 (the last time the USGS estimated total water consumption in the U.S.), thermoelectric power plants withdrew 38.7 percent (132 BGD) of the total water used, but only consumed 2.5 percent (3.3 BGD). Figure 4 below shows water withdrawals and water consumption in 1995 by water-use category (USGS, 1998).

Figure 4. U.S. Water Withdrawals and Consumption by Water-Use Category in 1995



(USGS, 2009)

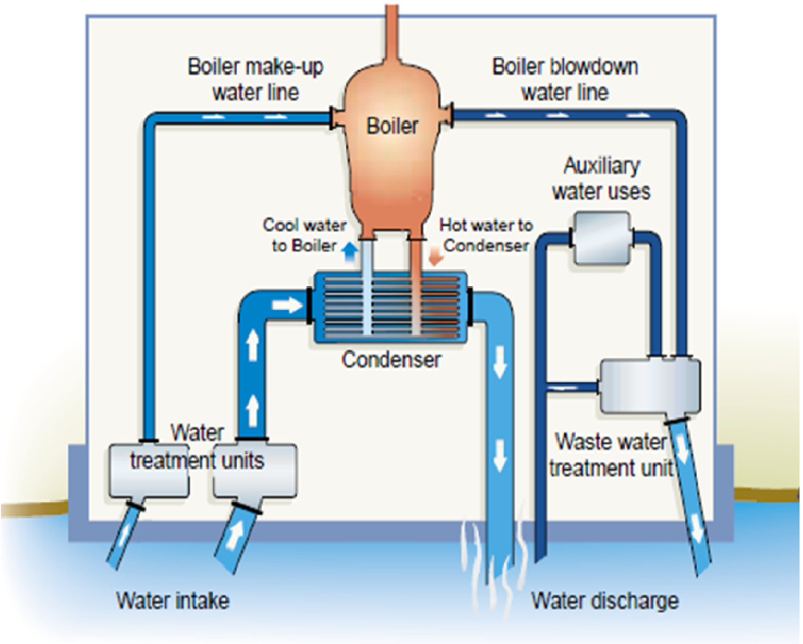
Thermoelectric power plants generate electricity using a heat source, either by burning fuels such as coal, oil, natural gas, or biomass/municipal solid waste or by fission inside of a nuclear reactor. These power plants use water to generate steam and to cool and condense the steam back to liquid form.

A thermoelectric power plant burns fuel in a boiler (a rectangular furnace). The heat from the fuel flows over tubes of water in the boiler and generates steam, which is then used to drive a turbine-generator. The exhaust steam from the turbine flows over tubes of cooling water in a condenser. As the steam flows over the cooling water, it drops in temperature and eventually condenses. The condensed steam (water) flows into pumps at the bottom of the condenser. These pumps recycle the water back into the boiler (see Figures 5, 6, and 8) (NETL, 2009).

Water Use

There are two types of conventional cooling systems: once-through cooling systems and recirculated cooling systems. In a once-through cooling system, depicted in Figure 5 below, also called an “open loop” cooling system, water is withdrawn from a water body source, passed through a condenser to absorb heat, and then discharged downstream (Sovacool & Sovacool, 2009b). Once-through cooling systems must withdraw a large amount of water from a water source, but consume only a small quantity of water (approximately 1 percent) via increased evaporation from the discharge water. Water that is released from the cooling system is at a higher temperature than the water in the receiving water body. This increase in temperature also increases evaporative losses in the receiving water body (EPRI, 2002).

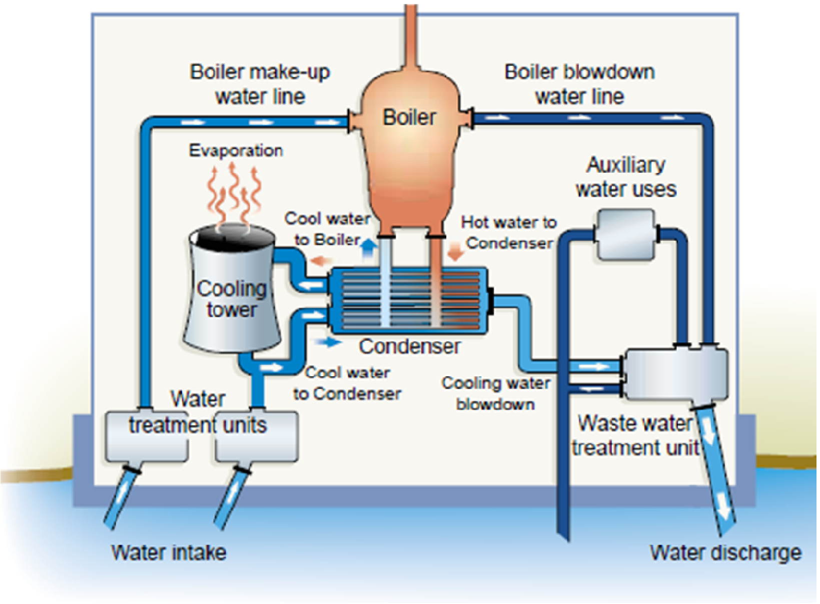
Figure 5. Once-through Cooling System



(Clean Air Task Force and the Land and Water Fund of the Rockies, 2003)

In a recirculating cooling system (depicted in Figure 6 below), also called a “closed loop” cooling system, water that passes through the condenser to absorb heat is sent through the system again, instead of discharged into water body. In order to prevent mineral and sediment buildup in the cooling water, the system discharges a portion of the water at regular intervals; this process is called blowdown. Plants that use closed loop systems must withdraw water from a water body to replace the water lost through evaporation and through blowdown (NETL, 2009).

Figure 6. Recirculating Cooling System

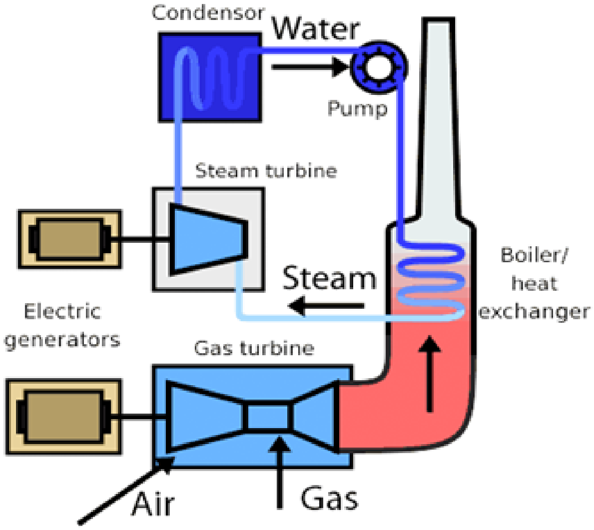


(Clean Air Task Force and the Land and Water Fund of the Rockies, 2003)

Recirculated cooling systems use either a cooling tower or a cooling pond to dissipate the heat from the cooling water to the ambient air. Plants that use a cooling tower pump the warm cooling water from the condenser to the cooling tower. When the cooling water interacts with the air it decreases in temperature. Some of the water evaporates, forming a water vapor plume that flows out of the cooling tower. The rest of the water flows back into the condenser. Plants that use a cooling pond pump the warm cooling water from the condenser into the cooling pond. The heat of the warm cooling water transfers from the pond to the atmosphere; evaporation also helps to cool the water. Cool water is pumped from the pond back into the condenser (NETL, 2009). Closed loop systems do not need to withdraw nearly as much water as open loop systems. But, because closed loop systems (typically) lose more water to evaporation and blowdown, they consume more water (Sovacool & Sovacool, 2009b).

A combined cycle power plant (depicted in Figure 7 below) uses a gas turbine, also called a combustion turbine. These plants send the waste heat from the gas turbine to the boiler or to a heat recovery steam generator to generate electricity, increasing the efficiency of the plant. Combined cycle plants can utilize either open or closed loop cooling systems. Generally, the water withdrawal from these plants is lower than a single cycle plant because only one third (roughly) of the net power output at a combined cycle plant is from the steam turbine (EPRI, 2002).

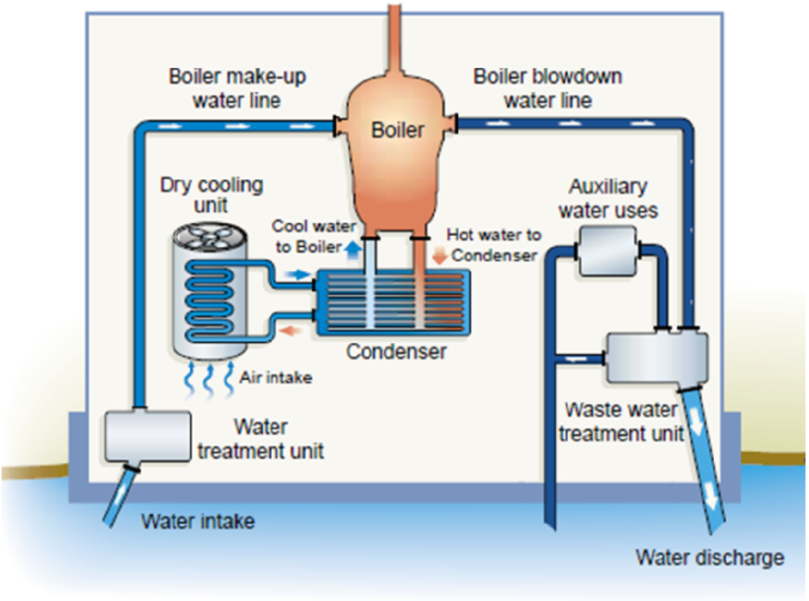
Figure 7. Combined Cycle Power Plant



(Guswhenta Developments, 2007)

Some combined cycle plants use dry cooling systems (depicted in Figure 8 below). Dry cooling tower systems do not require cooling water. Instead, the hot water passes from the condenser to a heat exchanger where heat is transferred to the ambient air (Fthenakis & Kim, 2010).

Figure 8. Dry Cooling System



(Clean Air Task Force and the Land and Water Fund of the Rockies, 2003)

Figure 9 below lists the typical withdrawal and consumption rates for natural gas combined-cycle power plants for the cooling system types described above.[3]

Figure 9. Water Withdrawal and Consumption Rates for Natural Gas Combined-Cycle Plants

Plant Type	Cooling System Type	Water Withdrawal (gal/MWh)	Water Consumption (gal/MWh)
Natural gas combined-cycle	Once-through cooling	9,010	20
	Recirculating	150	130
	Cooling pond	5,950	240
	Dry cooling	4	4

(NETL, 2009)

It is important to note that the withdrawal and consumption rates presented in Figure 9 are estimates. The exact amount of water required by a power plant will vary by location and will depend primarily on the average temperature and humidity at the plant site and the quality of water used at the plant (NREL, 2002).

Life Cycle Analysis

The impact of thermoelectric power on water resources extends beyond the water used at the power plant. The extraction, purification, transportation, and storage of natural gas as well as the construction of the plant and the manufacturing of equipment used at the plant also require water. Figure 10 below shows the amount of water consumed and withdrawn in the preparation of natural gas used at thermoelectric power plants in the U.S. In the figure, “upstream” water usage refers to the water withdrawals embedded in the materials and energy.

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[3] For coal-fired plants, the water withdrawal and consumption factors were based on the sum of three components: 1) boiler make-up water; 2) flue gas desulfurization (FGD) make-up water; and 3) cooling water. Average water withdrawal (gal/hr), average water consumption (gal/hr), and summer capacity were used to calculate average withdrawal and consumption scaling factors (gal/kWh) for each model plant in each of the regions. Nuclear, oil steam, gas steam, and natural gas combined-cycle plants were classified according to region, cooling water source (fresh or saline), and cooling water system (recirculating or once-through).

Figure 10. Upstream Water Consumption and Withdrawal Rates for Natural Gas

Fuel	Stage	Withdrawal (gal/MWh)	Withdrawal upstream (gal/MWh)	Consumption (gal/MWh)
Natural gas	Extraction – on shore	34	79	Negligible
	Extraction – off shore	0.21	0.11	Negligible
	Purification	17	Not available	15
	Pipeline transportation	0.40	10	8
	Underground storage	Not available	4	Not available
	Power plant environmental control	Not available	235	Not available

(Fthenakis & Kim, 2010)

The average[4] life-cycle water withdrawal for natural gas combined cycle plants in the U.S. is 1,060 gallons per MWh (approximately 21 bath tubs[5] per MWh). This number represents the best estimate based on data reported by power plants in the U.S. to the National Energy Technology Laboratory (NETL). The estimate may be misleading, however, because only 7 percent of combined-cycle power plants in operation reported data to NETL. If all plants were to report data, it is very likely that dry cooling would represent a much smaller percentage of total combined cycle cooling, increasing the average life-cycle water withdrawal for plants in the U.S. (NETL, 2009). On-site cooling during electricity generation is the most water intensive stage of the life cycle (Fthenakis & Kim, 2010).

Water Quality

Thermoelectric power plants can affect the water quality of the lakes, rivers, and streams they use as a water source. Plants with once-through cooling systems return heated water to the water source. Water temperature deltas (i.e., large temperature differences between intake and discharge waters) can alter the chemical composition of the water source and increase the occurrence of eutrophication. Severe or prolonged instances of eutrophication can damage ecosystems, decrease the aesthetic and recreational value of the water body, and complicate drinking water treatment (Sovacool & Sovacool, 2009b).

Plant operators typically add chlorine to intake water to control microbes that can corrode pipes. Cooling water discharged from a thermoelectric power plant, regardless of the type of cooling system employed by the plant, contains trace amounts of chlorine and its by-products. Chlorine can be toxic to aquatic life, even at low concentrations; chlorine and biocide discharges are subject to state and federal water quality standards. In addition, high water temperatures can magnify the impacts of chlorine (Clean Air Task Force and the Land and Water Fund of the Rockies, 2003).

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[4] The life-cycle water withdrawals depend on the type of cooling system each plant uses. Fthenakis and Kim calculated the average withdrawals per thermoelectric fuel type using data from NETL. NETL determined that the percentages of cooling type for natural gas combined cycle plants are as follows: 30.8% recirculating, 8.6% once-through, 59% dry, and 1.7% cooling pond.

[5] Assume one bath tub holds 50 gallons of water.

Water that is reused in a close loop cooling system requires more chemical treatment to eliminate solids and salts that accumulate as the water evaporates. Water returned to its source after blowdown in plants with a closed loop cooling system that uses a cooling tower thus contains more dissolved and suspended solids than water used in once-through cooling systems (Sovacool & Sovacool, 2009b).

Boiler blowdown (water purged periodically from the boiler) and cleaning wastes from thermoelectric plants can contain trace amounts of copper, iron, nickel, zinc, chromium, and magnesium and are sent to a wastewater treatment facility. Additional sources of water discharge at the power plant site include: coal pile runoff, water used for coal cleaning, and water used to dilute waste from air emissions control devices (Clean Air Task Force and the Land and Water Fund of the Rockies, 2003).

Solar PV

The operation of solar PV technologies requires water, which is used to clean and cool the wafers, cells, and modules. Looking at the entire life cycle of a PV panel, the production and processing of raw materials (upstream processes) and the manufacturing process used to make the panel require water.

Figure 11. Water Withdrawals and Consumption for PV Technologies

	Manufacturing withdrawals (gal/MWh)	Upstream withdrawals (gal/MWh)	On-site withdrawals during operation (gal/MWh)	On-site consumption during operation (gal/MWh)	Notes
Frame	Not available	17	N/A	N/A	Based on multi-Si PV
Balance of system (BOS)	0.40	55	N/A	N/A	Based on ground-mount multi-Si PV
Multi-Si panel	53	388	N/A	N/A	Efficiency = 13.2%
Mono-Si panel	51	404	N/A	N/A	Efficiency = 14%
CdTe panel	0.21	152	N/A	N/A	Efficiency = 10.9%
Cleaning			4	4	

Assumptions: insolation 1800 kWh/m^2/year, lifetime of 30 years, performance ratio of 0.8

(Fthenakis & Kim, 2010)

Figure 11 above compares the water withdrawals and consumption rates of PV panel manufacturing and operation for three common PV technologies: multi-crystalline silicon (multi-Si), mono-crystalline silicon (mono-Si), and thin film cadmium telluride (CdTe). Silicon-based PV panels require more PV material than CdTe panels and thus need more water to produce.

Figure 11 provides withdrawal rates in gal/MWh so that they can be compared directly to the rates of a natural gas combined-cycle plant. These rates are specific to a panel with a 30 year life and a performance ratio of 0.8 located in an area with an insolation of 1800 kWh per m^2 per year. The actual amount of water withdrawn over the life cycle of a solar PV panel depends on the size and quantity of the modules and the material used to make the modules. Figure 12 below uses the data and assumptions in Figure 11 to convert the withdrawal rates from to gal/$m^2$of modules. These rates can be used in any area, regardless of insolation, assuming the panel type is equivalent on a per m^2 basis.

Figure 12. Water Withdrawals and Consumption for PV Technologies

	Manufacturing withdrawals (gal/ m^2)	Upstream withdrawals (gal/ m^2)	On-site withdrawals during operation (gal/ m^2/year)	On-site consumption during operation (gal/ m^2/year)	Notes
Frame	Not available	96	N/A	N/A	Based on multi-Si PV
Balance of system (BOS)	9	2	N/A	N/A	Based on ground-mount multi-Si PV
Multi-Si panel	301	2,215	N/A	N/A	Efficiency = 13.2%
Mono-Si panel	304	2,445	N/A	N/A	Efficiency = 14%
CdTe panel	1	715	N/A	N/A	Efficiency = 10.9%
Cleaning			1.1	1.1	

Looking across the entire life cycle of a PV panel, the total water withdrawn is 4.29 gallons per m^2 for CdTe panels, 6.55 gallons per m^2 for mono-Si panels, and 6.29 gallons per m^2 for multi-Si panels. The majority of the water is used upstream (embodied in the materials) and in the production of the panels. (Fthenakis and Kim did not have sufficient upstream data to compare water consumption over the entire life cycle) (Fthenakis & Kim, 2010). The upstream water use for panel production is mostly from electricity generation. The electricity used to produce silicon and to grow single crystals is generated primarily from thermoelectric power plants, which are water intensive (see Appendix B) (Kim, 2010).

Summary

Figure 13 below summarizes the water use data presented in the above sections.

Figure 13. Water Withdrawals and Consumption – Thermoelectric and Renewable Power[6]

		ELECTRICITY GENERATION ONLY		TOTAL LIFE CYCLE
		Water Withdrawal (gal/MWh)	Water Consumption (gal/MWh)	Water Withdrawal (gal/MWh)
Natural gas combined-cycle	Once-through cooling	9,010	20	1060[7]
	Recirculating	150	130	
	Cooling pond	5,950	240	
	Dry cooling	4	4	
Solar PV	Multi-Si	4	4	514
	Mono-Si	4	4	527
	CdTe	4	4	225

(Fthenakis & Kim, 2010)

Natural gas combined-cycle plants that use wet cooling systems withdraw and consume significantly more water per MWh than solar PV panels during electricity generation. Looking at the entire life cycle, the average natural gas combined-cycle plant in the U.S. withdraws twice as much water as a multi-Si PV panel and five times as much water as a CdTe PV panel. (Fthenakis and Kim did not have sufficient upstream data to compare water consumption over the entire life cycle.)

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[6] Estimates of the U.S. average water withdrawal for the natural gas combined fuel cycle is based on DOE data and U.S. statistics; the latter finds that around 20% of natural gas is produced by offshore extraction. NETL data are used for the operational stage of this fuel cycle.

[7] As explained earlier in this chapter, 1060 gal/MWh represents the best estimate based on data reported by power plants in the U.S. to NETL. The estimate may be misleading, however, because only 7 percent of combined-cycle power plants in operation reported data to NETL. If all plants were to report data, it is very likely that dry cooling would represent a much smaller percentage of total combined cycle cooling, increasing the average life-cycle water withdrawal for plants in the U.S.

Future Water Use for Electricity Generation

Electricity generation in the U.S. has increased steadily since 1950 and will most likely continue to rise in the future. Each year the EIA publishes a projection and analysis of energy supply, demand, and prices in the U.S. for the next 20 years. In the *Annual Energy Outlook* released in 2010, the EIA predicts that total energy demand in the U.S. will increase by 30 percent (an average of 1.0 percent per year) between 2009 and 2035. In order to meet growing demand and to compensate for the expected retirement of 45 gigawatts (GW) of existing capacity, the electric power sector will need to add 250 GW of new generating capacity during this period. The EIA predicts that the new capacity additions will be met by constructing power plants that use: natural gas (46 percent), renewables (37 percent), coal (12 percent), and nuclear energy (3 percent) (U.S. EIA, 2010a).

Despite this increase in electricity generation, the water withdrawals associated with thermoelectric power stabilized in the 1990s. Since 1950, the electricity sector has increased power output by a factor of twelve (U.S. EIA, 2009), but the water withdrawn to produce every kWh has fallen from 63 to 23 gallons (USGS, 2009). Cooling system improvements and water conservation efforts over the last half century enabled electric utilities to use water more efficiently. In addition, some power plants in the western U.S. treat impaired or reclaimed water (typically secondary-treated municipal wastewater, passively treated coal mine drainage, and ash pond effluent) to use in cooling cycles[8] (Sovacool & Sovacool, 2009b).

Even with dramatic changes in water use efficiency, energy infrastructure in the U.S. depends heavily on the availability of water. In order to construct new power plants, electric utilities must find sites with reliable water supplies. Congress asked the U.S. General Accounting Office (GAO) to identify current conditions and future trends to U.S. water availability and use. According to GAO's 2003 report:

> National water availability and use has not been comprehensively assessed in 25 years, but current trends indicate that demands on the nation's supplies are growing. In particular, the nation's capacity for storing surface-water is limited and ground-water is being depleted. At the same time, growing population and pressures to keep water instream for fisheries and the environment place new demands on the freshwater supply. The potential effects of climate change also create uncertainty about future water availability and use. (U.S. GAO, 2003)

The GAO report also emphasizes that forecasting water use is very difficult. Water availability and use depend on many factors: the ability to store and distribute water, demographics, social values, technological advances, environmental laws, and the magnitude and efficacy of conservation efforts. In addition, water availability varies significantly across regions in the U.S., complicating resource projections.

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[8] For additional information about the use of impaired water in thermoelectric power cycles, see EPRI's 2003 report, Use of Degraded Water Sources as Cooling Water in Power Plants (EPRI 1005359). http://www.energy.ca.gov/reports/2004-02-23_500-03-110.PDF.

Recent reports published by NETL, the Electric Power Research Institute (EPRI), and a research team at the National University of Singapore (B.K. Sovacool and K.E. Sovacool) attempt to predict water resource availability and to pair these predictions with energy demand projections. While NETL finds that forecasted increases in electricity generation will not impact daily freshwater withdrawals in the future, the EPRI and Sovacool results show that rising competition for water resources, particularly in the west, southwest, and southeast could threaten the availability of water for power generation in certain areas. The sections below summarize the methodology and results of the NETL, EPRI, and Sovacool studies.

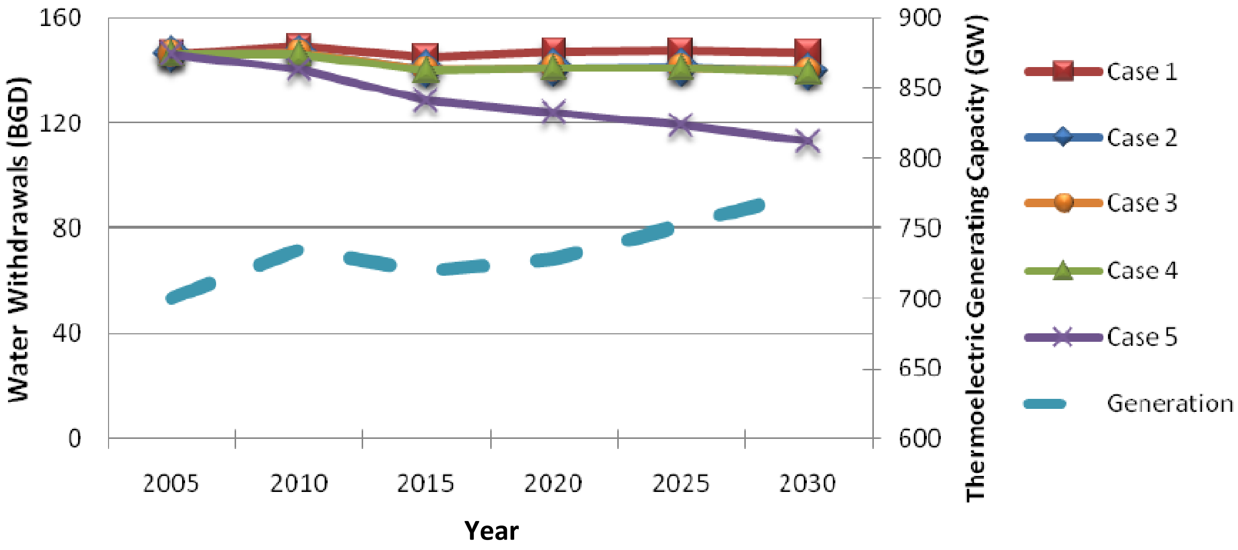
Future Freshwater Scenarios – National Energy Technology Laboratory (2009)

NETL used current power plant withdrawal and consumption factors and regional projections for electric power capacity additions and retirements to estimate future freshwater withdrawal and consumption requirements for the U.S. thermoelectric generation sector over five scenarios. The five scenarios (described below) cover the range of possible design choices for new power plants.

Scenario	Description	Rationale
1: Status quo scenario	Additions and retirements proportional to current water source and type of cooling system.	Assumes additions and retirements follow current trends.
2: Regulatory-driven scenario	All additions use freshwater and wet recirculating cooling; retirements proportional to current water source and cooling system.	Assumes 316(b) and future regulations dictate use of recirculating systems for all new capacity. Retirement decisions hinge on age and operational costs rather than water source and type of cooling system.
3: Regulatory-light scenario	90% of additions use freshwater and wet recirculating cooling; 10% of additions use saline water and once-through cooling. Retirements proportional to current water source and cooling system.	New additions favor use of freshwater recirculating systems, but some saline capacity is permitted. Retirement decisions remain tied to age and operational costs, tracking current source withdrawals.
4: Dry cooling case	25% of additions use dry cooling; 75% of additions use freshwater and wet recirculating cooling. Retirements proportional to current water source and cooling system.	Regulatory and public pressures result in significant market penetration of dry cooling technology. Retirement decisions remain tied to age and operational costs, tracking current source withdrawals.
5: Conversion scenario	Additions use freshwater and wet recirculating cooling; retirements proportional to current water source and cooling system. 5% of existing freshwater once-through cooling capacity retrofitted with wet recirculating cooling every 5 years starting in 2010.	Same as Scenario 2, except regulatory and public pressures compel state agencies to dictate the conversion of a significant amount of existing freshwater once-through cooling systems to wet recirculating.

In 2005, the average daily national freshwater withdrawal for thermoelectric power generation was 146 BGD. NETL's analysis projects that withdrawals for thermoelectric power generation will decrease to between 113 and 139.9 BGD by 2030 across scenarios 2 through 5; scenario 1 predicts a slight increase to 146.8 BGD. Figure 14 below presents these results.

Figure 14. Average National Freshwater Withdrawals for Thermoelectric Power Generation (BGD)

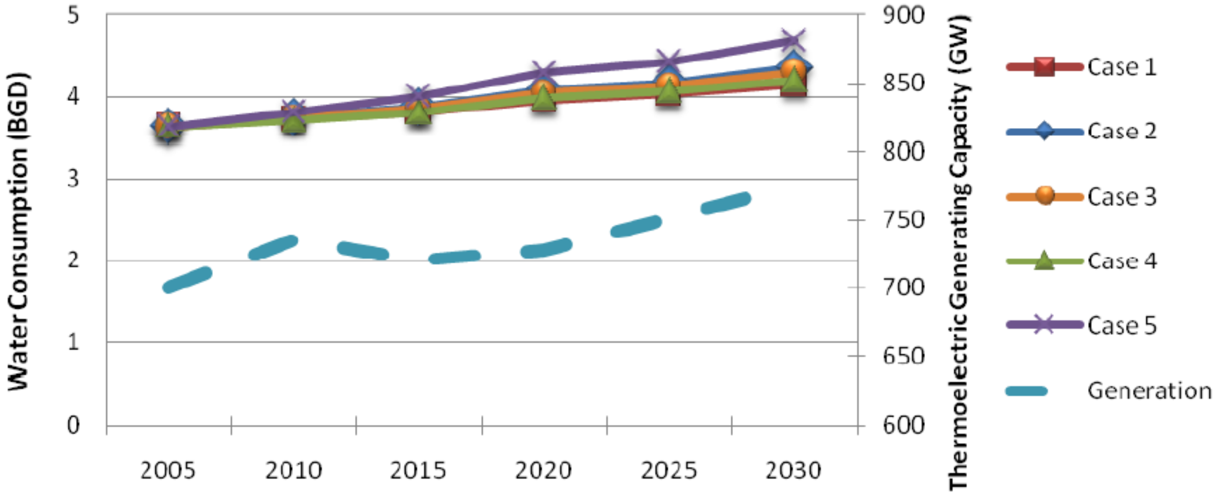


Data Used in Chart Above:

	2005	2010	2015	2020	2025	2030
Case 1	146.3	149.2	145.1	147.4	147.6	146.8
Case 2	146.3	146.4	140.5	141.1	141.3	139.9
Case 3	146.3	146.4	140.5	141.1	141.2	139.8
Case 4	146.3	146.2	140.2	140.7	140.9	139.4
Case 5	146.3	140.5	128.6	123.9	119.1	113.0

NETL's analysis also projects that average daily freshwater consumption resulting from U.S. thermoelectric power generation could range from 4.2 to 4.7 BGD by 2030, an increase from the 1995 baseline of 3.3 BGD. Figure 15 below presents these results.

Figure 15. Average National Freshwater Consumption for Thermoelectric Power Generation (BGD)



Data Used in Chart Above:

	2005	2010	2015	2020	2025	2030
Case 1	3.6	3.7	3.8	4.0	4.0	4.2
Case 2	3.6	3.8	3.9	4.1	4.2	4.4
Case 3	3.6	3.7	3.9	4.1	4.1	4.3
Case 4	3.6	3.7	3.8	4.0	4.1	4.2
Case 5	3.6	3.8	4.0	4.3	4.4	4.7

On a national basis, NETL’s analysis indicates that forecasted increases in electricity generation will not impact daily freshwater withdrawals in the future. While the amount of water consumed by the thermoelectric power sector will likely increase in the future, the amount is relatively small compared to other sectors (NETL, 2009).

Water Supply Indices – Electric Power Research Institute (2003)

Several years ago, EPRI identified water availability as a major factor influencing power development in the U.S. Since then EPRI has published several reports and guidance to help utilities understand and manage the interrelationship of water and energy. *A Survey of Water Use and Sustainability in the United States with a Focus on Power Generation*, published by EPRI in 2003, uses two composite metrics to identify regions of concern from the viewpoint of water sustainability and thermoelectric cooling water availability.

EPRI used data from USGS, EIA, Water Resources Council, U.S. Census Bureau, and U.S. Department of Agriculture to project withdrawal requirements and water demand at the county-level across the U.S.

EPRI synthesized this data into two metrics: water supply sustainability and thermoelectric cooling constraint.[9]

EPRI's water supply sustainability index highlights areas where water supply issues in general are likely to be a concern. The index evaluates water supply constraints based on the metrics representing six types of criteria.

Criteria	Metric
Extent of development of available renewable water	Greater than 25% of available precipitation currently used
Sustainable groundwater use	Ratio of groundwater withdrawal to available precipitation is greater than 50 percent
Environmental regulatory limits on freshwater withdrawals	Two or more endangered aquatic species[10]
Susceptibility to draught	Summer deficit during low precipitation is greater than 10 inches
Growth of water use	Business as usual requirements to 2025 increase current freshwater withdrawal by more than 20%
New requirements of storage or withdrawal from storage	Summer deficit increases more than 1 inch over 1995-2005

EPRI places counties into one of four classifications: a highly susceptible county meets four or more criteria above; a moderate susceptible county meets three criteria; a susceptible county meets two of the criteria; and a susceptibility less likely county meets either one criteria or no criteria. Figure 16 below shows a map of the water supply sustainability index. Highly susceptible counties are concentrated in the southwestern U.S., notably California, Nevada, Arizona, and New Mexico.

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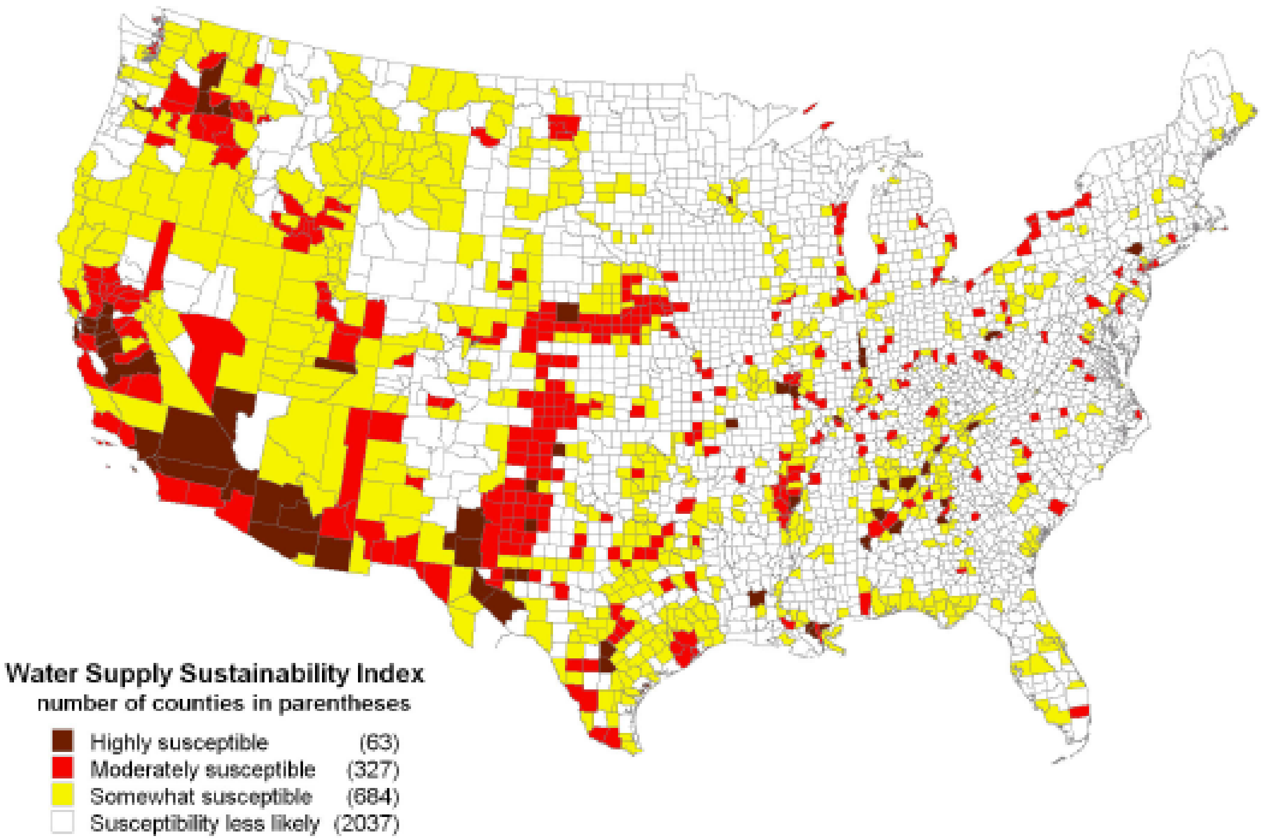
[9] While EPRI reports results at the county level, the EIA forecasts are reported at the census division level, which comprises several states. EPRI took the following steps and made the following assumptions in order to disaggregate the data to the county level: (1) applied actual state level change from 1995 to 2000 to all counties within a state that had any form of power generation; (2) applied forecast percent increase in generation from 2000 to 2025 to all counties within a census division that had any form of power generation; (3) did not allocate new generation to counties that do not have generation at present; and (4) assumed all new power generation is thermoelectric.

[10] Although water withdrawals are limited by several federal and state regulations, these cannot be represented in a simply way over the entire country. Instead, EPRI chose to designate a surrogate that represents the regulatory limits to freshwater withdrawals: the number of endangered aquatic species present in each county across the U.S.

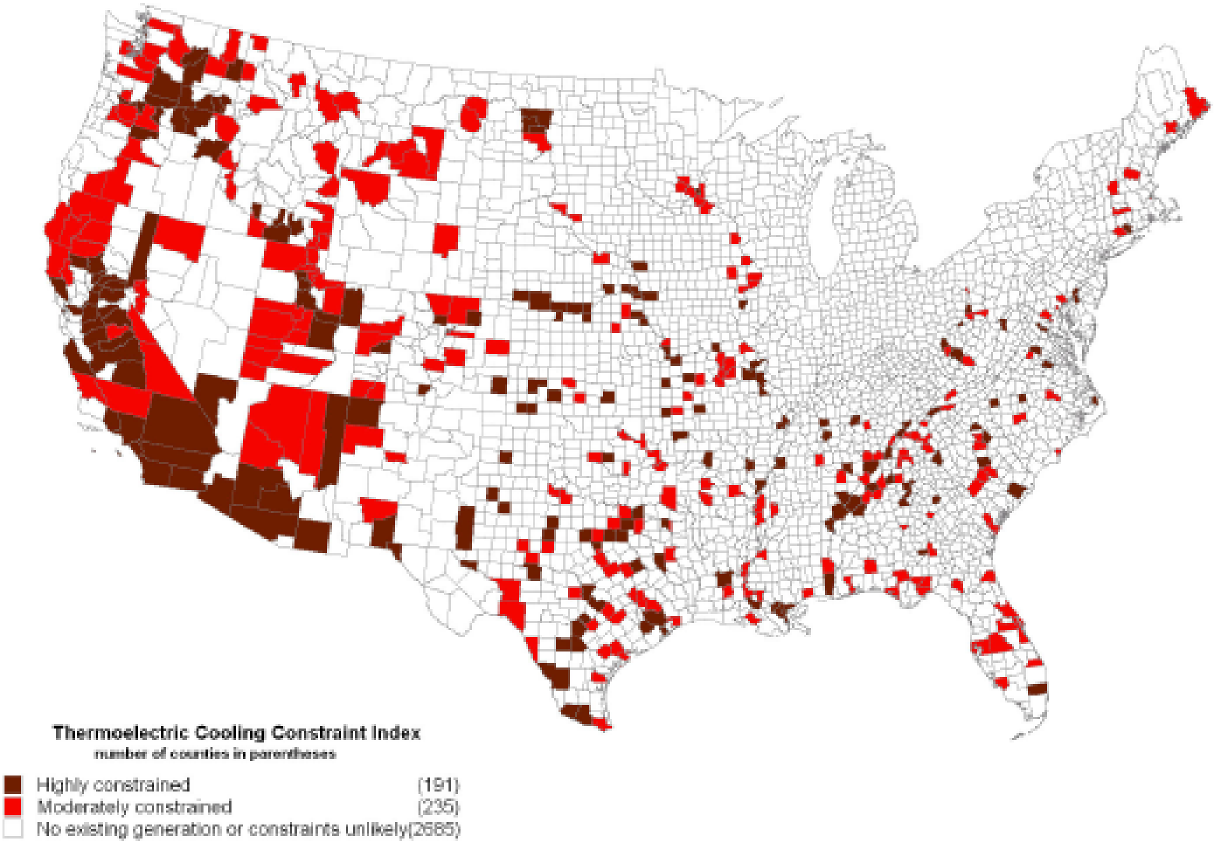
Figure 16. Water Supply Sustainability Index



EPRI's thermoelectric cooling water supply limitation index highlights areas where electricity growth may be constrained by available water supplies. The index includes three designations: highly constrained, moderately constrained, and no existing generation or constraints unlikely. If the 2025 electricity generation forecast predicts an increase of more than 50 percent in a county and the county has a water supply sustainability index of 3 or more, the county is considered to be highly constrained. If the 2025 electricity generation forecast predicts an increase of more than 50 percent in a county and the county has a water supply sustainability index of 2, the county is considered to be moderately constrained.

Figure 17 below shows a map of the thermoelectric cooling index. Highly constrained areas are concentrated in the western U.S., notably California, Washington, Arizona, and Texas.

Figure 17. Thermoelectric Cooling Water Supply Limitation Index



It is important to note that EPRI predicted the water needs of new thermoelectric power plants using the current rate of water use in a given county. This assumes that the current distribution of cooling system types will remain constant in the future. In reality, new power plants will likely use less water than the average U.S. power plant, especially if more efficient cooling technologies emerge in the future.

While EPRI notes that water stressed areas will most likely be more vulnerable to climate change, their assessment did not make quantitative assessments of the climate change impacts on water resources on a national scale. In addition, storage, local water regulations, and water rights information can affect water sustainability. EPRI excluded these data from their analysis because they were not available in a consistent format (EPRI, 2003).

Electricity Water Crises Areas – Sovacool & Sovacool (2009)

Sovacool and Sovacool predicted the likelihood of water shortages in the U.S. by 2025. They modeled population growth, power plant construction, and water supply and demand at the county level for the period 2000 to 2050 using data from the U.S. Census Bureau, the EIA, and the USGS.

The model assumes that all new generation is thermoelectric and relies on a mix of once-through and recirculated cooling systems. Additional assumptions include:

- 25 gallons used per kWh electricity generated (24.5 gallons withdrawn, 0.5 gallons consumed)
- Power plant operates 24 hours per day and 365 days per year
- Power plant operates at a capacity factor of 90 percent
- Water for power plant is "used" within the county
- Only include counties that currently generate power (counties with no current electricity generation were not allocated new generation)

The results of the model show that 22 U.S. counties covering 20 major metropolitan areas will experience severe water shortages related to electricity generation. The counties that are most at risk have a combination of rapid population growth and increases in thermoelectric generation and summer water deficits. (Summer water deficit is the difference between water supply and water demand during the summer months of July, August, and September.) Figure 18 below lists these at risk counties, termed "National Electricity-Water Crisis Areas," in rank order.

Figure 18. National Electricity-Water Crisis Areas

Rank	County	State	Total electricity in 2025 (MW)	Pop. growth 1995-2025 (per sq mile)	Summer water deficit in 2025 (inches)	Metropolitan area
1	Mecklenburg	NC	17,950	1528	28.7	Charlotte, NC
2	Lake	IL	12,987	1064	18.1	Chicago, IL
3	Will	IL	27,399	806	16.7	Chicago, IL
4	Queens	NY	11,613	8056	12.7	New York, NY
5	Cobb	GA	3480	2049	9.3	Atlanta, GA
6	Dallas	TX	6170	1437	6.6	Dallas, TX
7	Coweta	GA	6180	510	5.6	Atlanta, GA
8	Denver	CO	4503	1925	5	Denver, CO
9	Montgomery	MD	3776	757	4.4	Washington, DC and Baltimore, MD
10	St. Charles	MO	3350	533	4.3	St. Louis, MO
11	Washington	MN	3203	632	4.2	St. Paul, MN
12	Bexar	TX	9222	555	3	San Antonio, TX
13	Calvert	MD	12,938	533	2.9	Washington, DC and Baltimore, MD
14	Harris	TX	4462	1179	2.4	Houston, TX
15	Tarrant	TX	2704	1170	2.3	Dallas, TX
16	Multnomah	OR	5402	548	2.2	Portland, OR
17	Contra Costa	CA	4759	678	2	San Francisco, CA
18	Fort Bend	TX	19,656	851	1.9	Houston, TX
19	Wake	NC	5967	1266	1.7	Raleigh, NC
20	Suffolk	MA	5062	1184	1.7	Boston, MA
21	Clark	NV	20,148	642	1.5	Las Vegas, NV
22	Montgomery	TX	2871	647	1.5	Houston, TX

In their report, Sovacool and Sovacool acknowledged the following shortcomings associated with their methodology:

- Ignores possibility of electricity imports and exports between counties.
- Assumes that water consumed at power plant leaves local water table entirely; some water lost to evaporative cooling may return to another part of the county through precipitation.
- Water use factor (25 gal/kWh) could change dramatically if the new generation energy mix differs from that used in the model. If utilities construct more nuclear plants, for example, the water use factor would increase; if natural gas plants and wind/solar projects continue to displace new coal-fired plants the water use factor would decrease.
- Water use factor could also change dramatically if cooling technologies that use less water are developed, commercialized, and widely adopted in the power sector.
- Capacity factor of 90 percent for all new plants may be optimistic; some thermoelectric power plants, both new and old, operate at a lower efficiency (Sovacool & Sovacool, 2009a) (Sovacool & Sovacool, 2009b).

Regional/State Specific Water-Energy Analyses

Several federal and state agencies, universities, and environmental non-governmental organizations published reports that examine the interplay between water resource availability and electricity generation in a specific state or region in the U.S.:

- Arkansas River Basin (Colorado & Kansas): (Western Resource Advocates, 2009)
- Arizona: (Arizona Water Institute, 2007), (Arizona Water Institute, 2009)
- California: (California Energy Commission, 2005), University of California (Dennen et al., 2007)
- Nevada: (Western Resource Advocates, 2008)
- Texas: University of Texas-Austin (King, Duncan, & Webber, 2008), (Stillwell, King, Webber, Duncan, & Hardberger, 2009)
- Southeastern states: Southern States Energy Board & University of Tennessee-Knoxville (Feldman, Slough, & Garrett, 2008), World Resources Institute (WRI, 2009)
- Western states: (Clean Air Task Force and the Land and Water Fund of the Rockies, 2003)

Conclusions

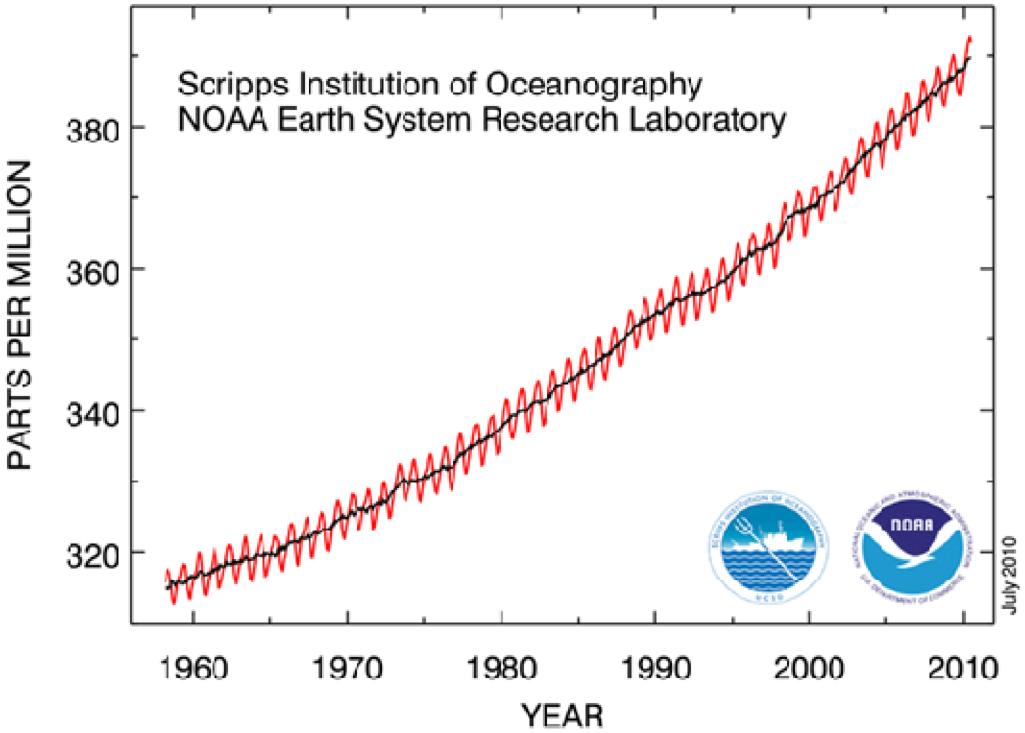
Water and energy are interdependent; the sustainable management of either resource must include the consideration of the other. While the water consumption of the electric power sector is minimal when compared to other sectors, thermoelectric power plants withdraw a significant amount of water and thus depend on reliable access to freshwater. Over the past decade, water resource constraints have prevented the construction of several power plants, particularly in the western U.S.

Freshwater availability varies widely by region and is difficult to forecast. While studies that examine the water resource implications of future electricity generation have limitations, they indicate that an increasing number of electric utilities in the U.S. will be affected by water scarcity. Certain renewable technologies, such as solar PV panels, withdraw and consume less water than thermoelectric power plants and can help to alleviate the electric power sector's dependency on this resource.

Chapter 2: CO_2 Emissions

CO_2) is a trace gas in the atmosphere that occurs at an average concentration of 391 parts per million (ppm) (NOAA, 2010). CO_2 is essential to respiration, the process by which plants produce oxygen. In the past fifty years the concentration of CO_2 in the atmosphere has grown rapidly with the spread of industrialization (see Figure 19). Industrial processes – primarily the combustion of fossil fuels –release CO_2 into the atmosphere at a rate that far exceeds the natural ability of the Earth's ecosystem to use or absorb it. Deforestation compounds this problem further as decreases in forest cover reduce the global carbon sequestration potential. Thus, CO_2 and other greenhouse gases are building up in the Earth's atmosphere.

Figure 19. Atmospheric CO_2 Levels at Mauna Loa Observatory (1960-2010)



(NOAA, 2010)

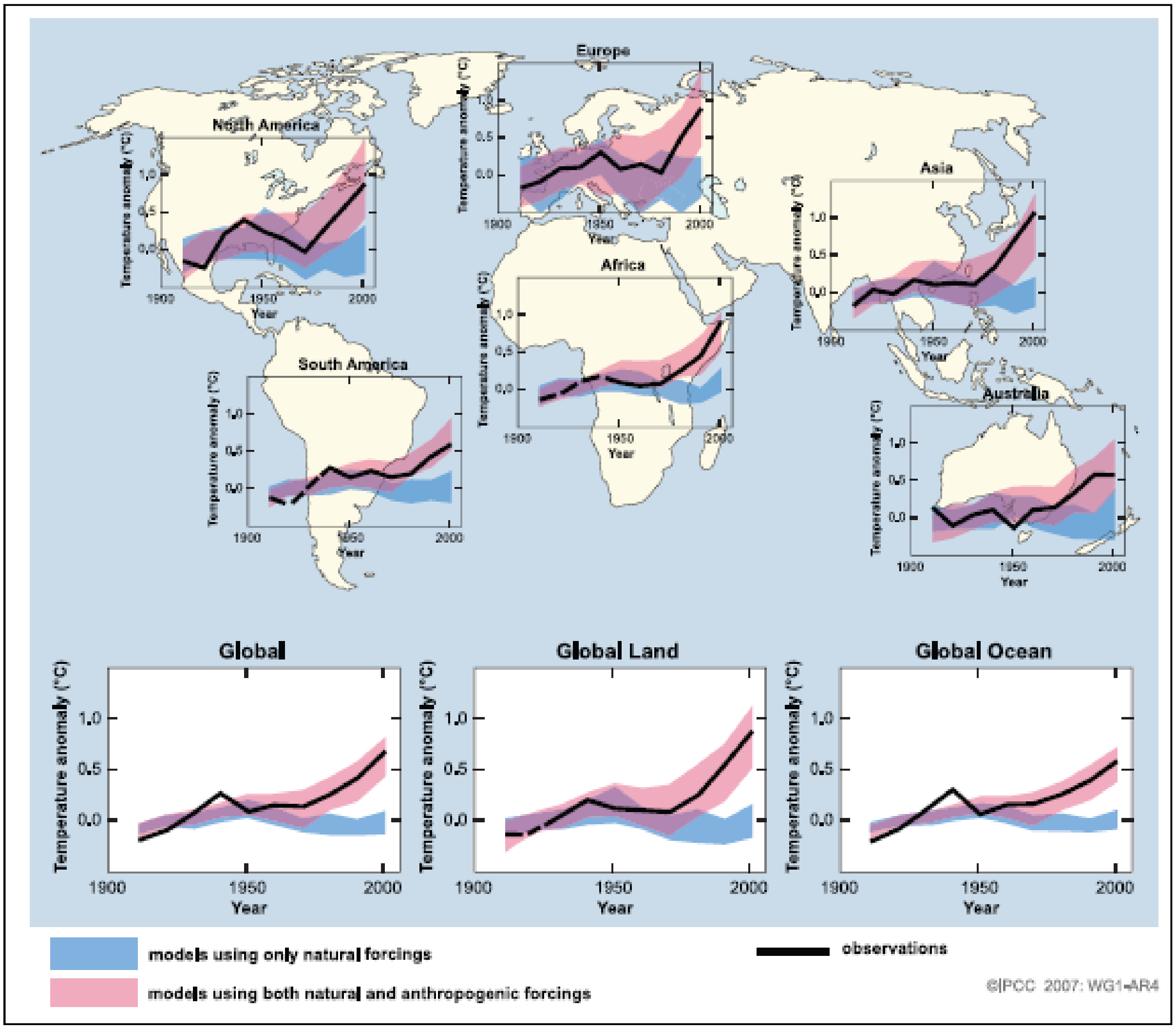
Controversy regarding CO_2 emissions arises over whether or not recent increases in atmospheric concentrations occurred naturally or are the result of human (anthropogenic) activities, mainly fossil fuel combustion. Additional disputes have emerged over the correlation between higher global carbon dioxide concentrations and increases in the average global temperature.

The Effects of CO_2 Emissions

According to the United Nation's Intergovernmental Panel on Climate Change (IPCC), "Warming of the climate is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. … Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations.” (IPCC, 2007)

Figure 20 shows the temperature increases between 1990 and 2000 for each continent.

Figure 20. Global and Continental Temperature Change



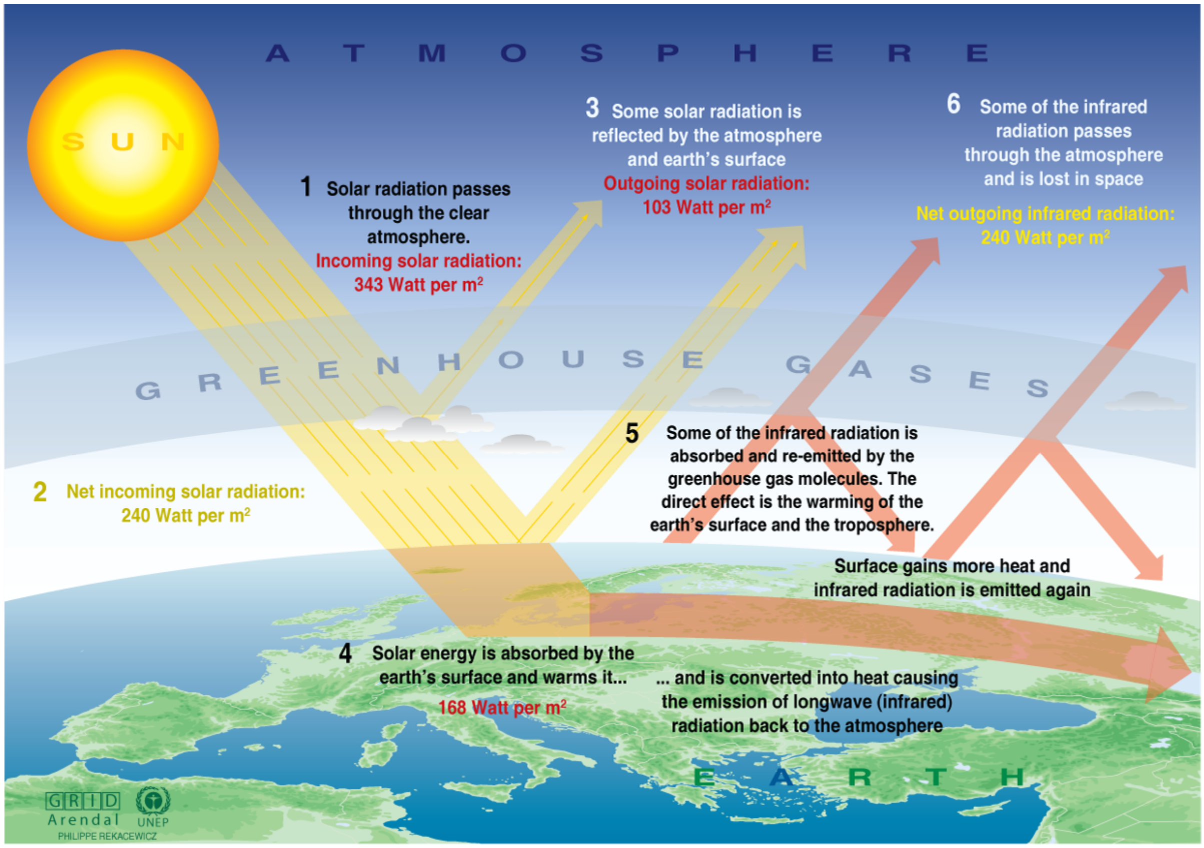
(IPCC, 2007)

The greenhouse effect (depicted in Figure 21 and explained in the steps below) describes the ability of the atmosphere to capture and retain heat emitted by the earth’s surface.

1. Solar radiation passes through the earth’s atmosphere at an average radiation level of 343 W/m_2
2. The actual solar radiation, or net incoming solar radiation, that passes through the layers of greenhouse gases is closer to 243 W/m_2
3. The earth’s surface and atmosphere reflect the remaining radiation (103 W/m_2)

4. The earth absorbs solar radiation (described in #2 above), converting it into heat and warming the surface. This heat returns to the atmosphere in the form of long wave infrared radiation.
5. Greenhouse gases trap some of this infrared radiation, further warming the earth's surface and troposphere. As the concentration of greenhouse gases increases, the amount of infrared radiation trapped in the atmosphere also increases.
6. Some of the reflected infrared radiation passes through earth's atmosphere and into space.

Figure 21. The Greenhouse Gas Effect

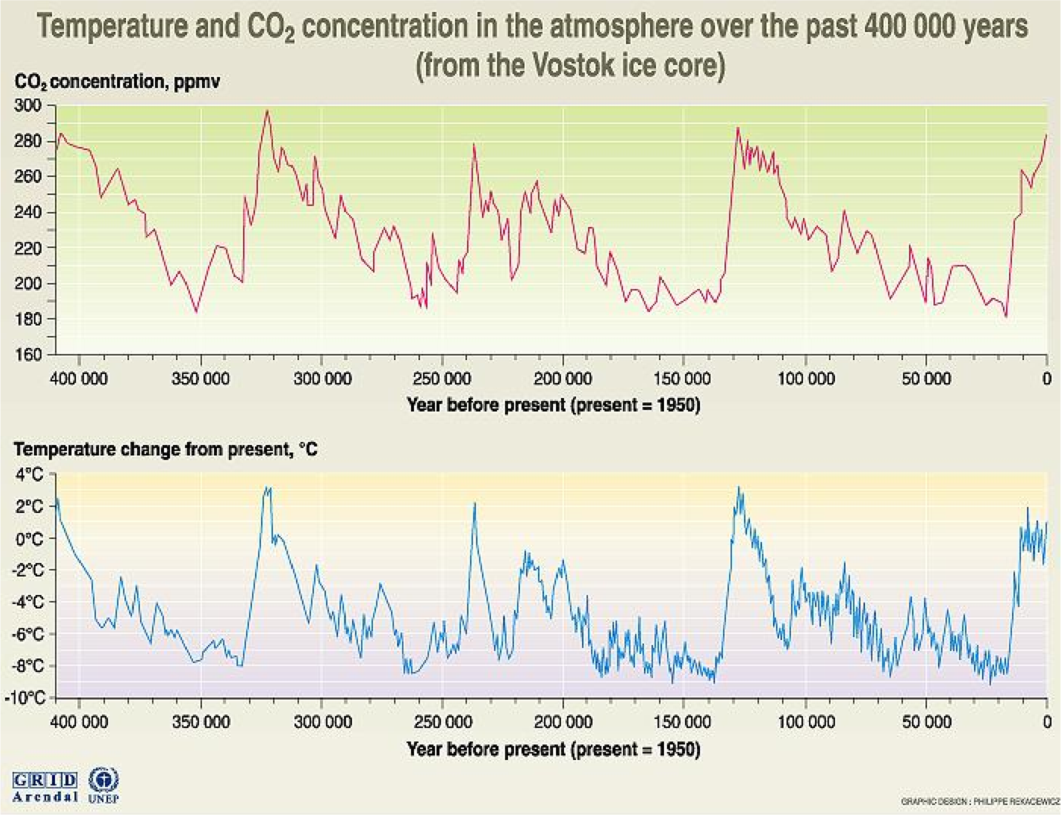


Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

(UNEP, 2001)

CO_2 is considered a greenhouse gas because it can retain heat and water vapor in the earth's atmosphere. Earth's historic CO_2 levels have fluctuated over time. Figure 22 below illustrates the strong correlation between atmospheric CO_2 levels and temperature highlighted in step five in Figure 21 above.

Figure 22. Temperature and CO_2 Correlation

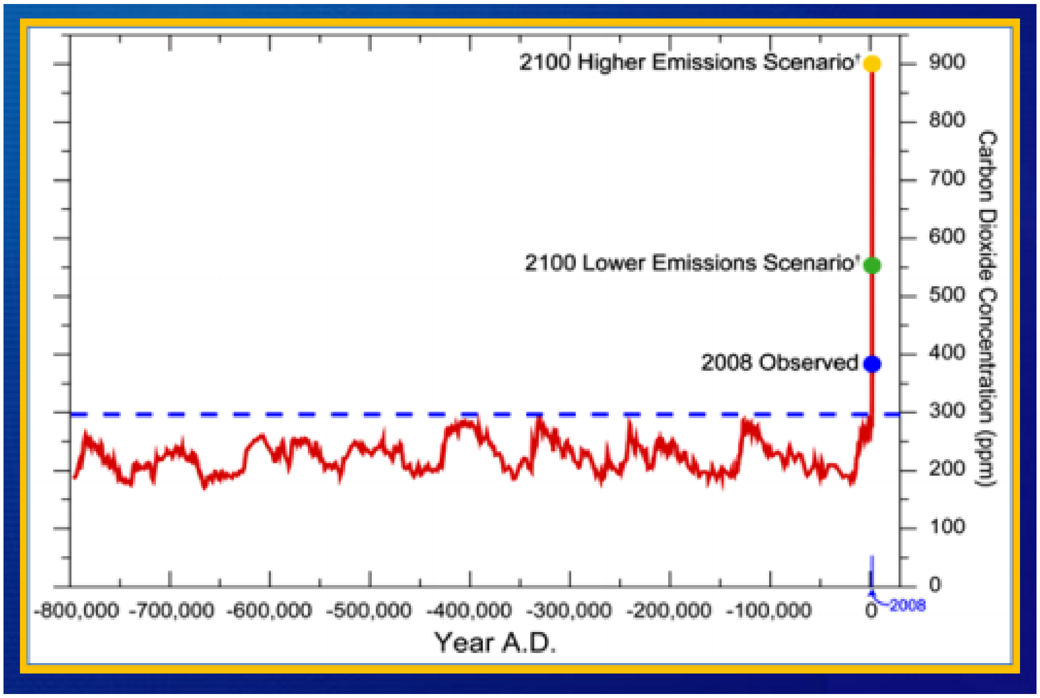


Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

(UNEP, 2001)

The difference, however, between the current increases in CO_2 levels and past changes is that recent changes are occurring at an unprecedented rapid rate. What normally takes well over 10,000 years to take place has unfolded within the past 50 to 100 years; and based on current estimates, the CO_2 levels could increase rapidly past historic maximum concentrations. Figure 23 below estimates atmospheric CO_2 concentrations assuming a business-as-usual approach to global carbon emissions. By the end of the century the concentration levels could very well be twice as high as the historical maximum in the past 400,000 years.

Figure 23. Historic Atmospheric CO_2 Concentrations



(Wuebbles, 2010)

The biological processes – including evolutionary changes in species adaptation that normally take many generations to occur – have not and will not be able to keep up with rapid climate changes. Without a stabilization of the atmospheric CO_2 levels the results of climate change on biodiversity could be catastrophic. It is unknown what the consequences will be for humans who are ultimately dependent on the Earth's natural resources for survival.

Other potential dangerous outcomes with climate change include:

- Increase in global sea level
- Detrimental and potentially deadly effects on the global agriculture sector
- Increase in severe weather events such as tropical cyclones, droughts and heat waves
- Regional unrest and turmoil over allocation of essential scarce resources such as water and food

According to the World Resources Institute, over 2.2 billion people or 39 percent of the world's population live within 100 kilometers of the coast (WRI, 2000). Incremental increases in global sea level caused by climate change are a significant risk for some of the world's most vulnerable populations.

CO_2 Emissions Avoided by Employing Solar Power

A NGCC plant emits more CO_2 per MWh than a solar PV plant. Figure 24 below shows the CO_2 emissions avoided per year by replacing natural gas with solar PV for a range of plant sizes.

Figure 24. CO_2 Emissions Avoided per Year (short tons CO_2)

MW Capacity[11]	MWh/year	CO_2 Emissions from NG	CO_2 Emission from Solar PV	Emissions avoided (NG – solar PV)
3	5,000	2,837.50	297.62	2,539.88
7	10,000	5,675.00	595.25	5,079.75
10	15,000	8,512.50	892.87	7,619.63
13	20,000	11,350.00	1,190.50	10,159.50
17	25,000	14,187.50	1,488.12	12,699.38
20	30,000	17,025.00	1,785.74	15,239.26
23	35,000	19,862.50	2,083.37	17,779.13
27	40,000	22,700.00	2,380.99	20,319.01
30	45,000	25,537.50	2,678.62	22,858.88
33	50,000	28,375.00	2,976.24	25,398.76
37	55,000	31,212.50	3,273.86	27,938.64
40	60,000	34,050.00	3,571.49	30,478.51
43	65,000	36,887.50	3,869.11	33,018.39
47	70,000	39,725.00	4,166.74	35,558.26
50	75,000	42,562.50	4,464.36	38,098.14
53	80,000	45,400.00	4,761.98	40,638.02
57	85,000	48,237.50	5,059.61	43,177.89
60	90,000	51,075.00	5,357.23	45,717.77
63	95,000	53,912.50	5,654.86	48,257.64
67	100,000	56,750.00	5,952.48	50,797.52

This analysis is based on emission factors for electricity generation using natural gas and for electricity generation using solar PV panels. An emissions factor is a measure of the amount of a pollutant released into the atmosphere relative to the intensity of a specific activity. The CO_2 emissions factor used for a NG[12] plant in the analysis above is 1,135 lbs CO_2 per MWh of electricity generation (U.S. EPA, 2007a).

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[11] Assumes a production factor of 1.5.

[12] The emissions factor of 1,135 lbs CO_2 per MWh is a national average for natural gas plants. This factor is not specific to a NGCC plant because reliable national averages for NGCC are not currently available.

As explained in the description of the impact analysis, all emissions associated with PV occur prior to its interconnection with the grid, primarily in the manufacturing phase. For the solar PV plant, the analysis uses an emissions factor of 54 g CO_2 per kWh used to manufacture crystalline silicon (the preferred technology for most ground-mounted solar PV developers) in the U.S. (Fthenakis, Kim, & Alsema, 2008).

CO_2 Price Sensitivity Analysis

The price of carbon directly affects an additional economic value of solar PV development. The U.S. does not have a mandatory national CO_2 emissions trading market but does have several regional GHG compliance markets: the Regional Greenhouse Gas Initiative in the Northeast and Mid-Atlantic, the Western Climate Initiative and the Midwestern Greenhouse Gas Reduction Accord in the central U.S. The prospect of comprehensive climate legislation in the U.S. and the recent global recession makes it difficult to predict the size and liquidity of future emissions markets, however.

CO_2 Price Forecasts

Although the structure and organization of CO_2 markets is uncertain, reliable data exists regarding the future price of CO_2 emissions. The state of California relies on the price forecasting of Synapse Energy Economics (a consulting firm) when calculating production based incentives for renewable energy projects. Figure 25 below shows the firm's CO_2 forecasts for 2008. The forecasted prices range from $10 per ton of carbon dioxide in 2013 – presumably under a scenario where the U.S. does not enact climate legislation – to a high of $68.40 in 2030.

Figure 25. Synapse 2008 CO_2 Price Forecasts

Year	Low	Mid	High
2013	$10.00	$15.00	$30.00
2014	$10.80	$17.30	$32.30
2015	$11.50	$19.50	$34.50
2016	$12.30	$21.80	$36.80
2017	$13.00	$24.00	$39.00
2018	$13.80	$26.30	$41.30
2019	$14.50	$28.50	$43.50
2020	$15.30	$30.80	$45.80
2021	$16.00	$33.10	$48.10
2022	$16.80	$35.30	$50.30
2023	$17.50	$37.60	$52.60
2024	$18.30	$39.80	$54.80
2025	$19.00	$42.10	$57.10
2026	$19.80	$44.30	$59.30
2027	$20.50	$46.60	$61.60
2028	$21.30	$48.80	$63.80
2029	$22.00	$51.10	$66.10
2030	$22.80	$53.40	$68.40

(Synapse Energy, 2008)

EcoSecurities, another energy consulting firm, projects a price range of \$20 to \$50 per ton of CO_2 between 2020 and 2030(EcoSecurities, 2009).

In 2009, The World Bank aggregated the price forecasts of several financial institutions. Figure 26 below shows the range of prices projections by Barclays Capital, Cheuvreux Credit Agricole Group and Société Générale in the European Union Emissions Trading Scheme (EU ETS). For Phase II (2008-2012), prices forecasted by the three banks ranged from 11€ to 23€ per metric ton of CO_2e (\$13 to \$27 per short ton[13]). Price forecasts for Phase III (2012-2020) range from 23€ to 40€ per metric ton of CO_2e (\$27-\$47 per short ton) (Capoor & Ambrosi, 2009).

Figure 26. Financial Institution Estimates of Future Carbon Prices (2009)

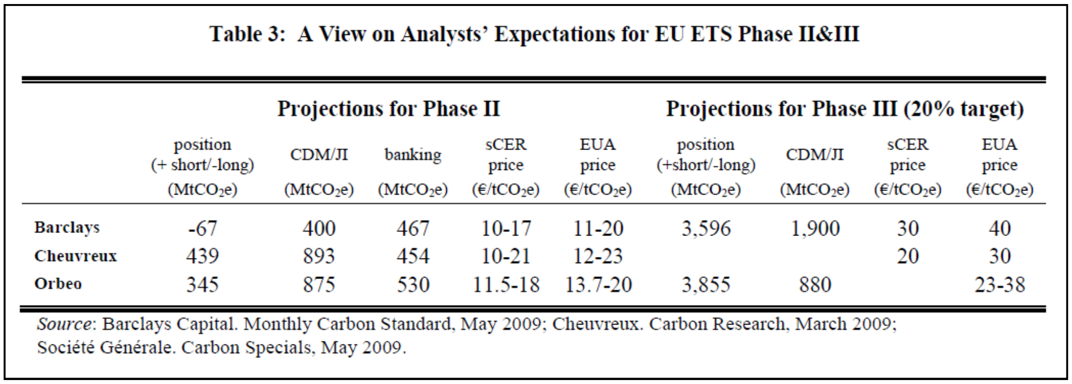

Table 3: A View on Analysts' Expectations for EU ETS Phase II&III

	Projections for Phase II					Projections for Phase III (20% target)			
	position (+ short/-long) ($MtCO_2e$)	CDM/JI ($MtCO_2e$)	banking ($MtCO_2e$)	sCER price (€/tCO_2e)	EUA price (€/tCO_2e)	position (+short/-long) ($MtCO_2e$)	CDM/JI ($MtCO_2e$)	sCER price (€/tCO_2e)	EUA price (€/tCO_2e)
Barclays	-67	400	467	10-17	11-20	3,596	1,900	30	40
Cheuvreux	439	893	454	10-21	12-23			20	30
Orbeo	345	875	530	11.5-18	13.7-20	3,855	880		23-38

Source: Barclays Capital. Monthly Carbon Standard, May 2009; Cheuvreux. Carbon Research, March 2009; Société Générale. Carbon Specials, May 2009.

(Capoor & Ambrosi, 2009)

In summary, each of these sources predicts carbon dioxide prices will be between \$10 and \$68 in the next 10 years. Broader economic factors, such as a stagnating global economy, could lead to a decrease in CO_2 emissions, lowering the price of CO_2 allowances.

Avoided Costs of CO_2 Emissions

In the states or regions included a CO_2 emissions market, the emissions avoided by generating electricity using solar PV (versus NGCC) can be converted to economic value. The sensitivity analysis in Figure 27 below shows the costs avoided (or cost savings) for a range of project sizes (in MWH/year) and carbon prices (in USD/short ton). The annual savings for a 3 MW project (5,000 MWh), for example are \$28,375 at a price of \$10 per ton of CO_2 and \$170,250 at a price of \$60 per ton of CO_2.

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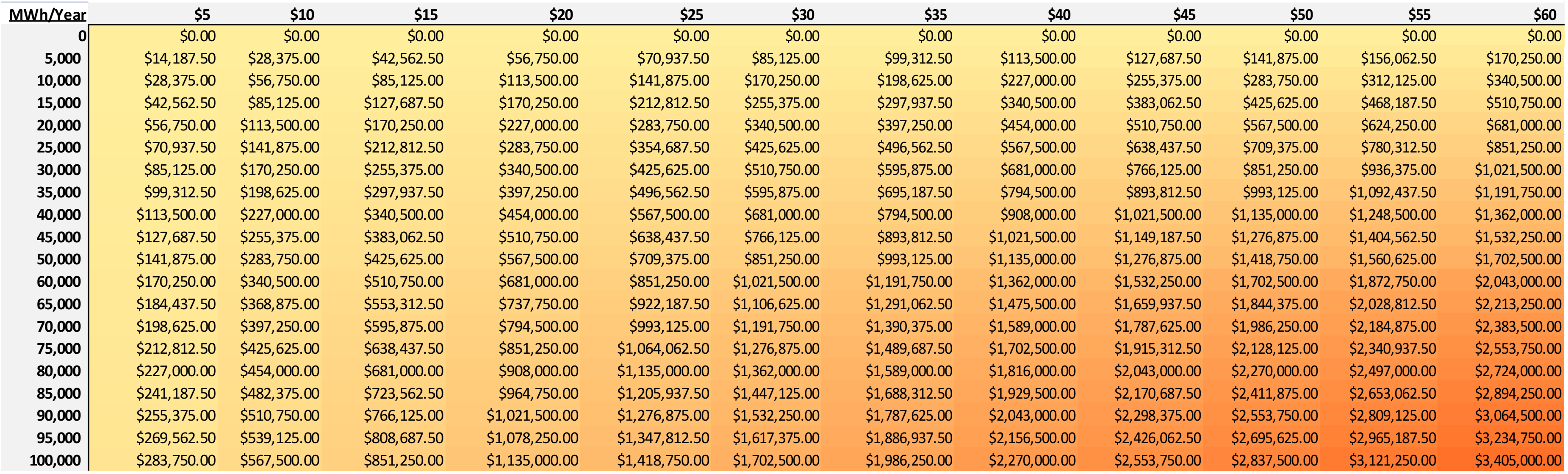
[13] As of July 29, 2010, one euro converts to \$1.30762. One metric ton is equivalent to 1.10231 short tons.

Figure 27. Cost Savings by Size of PV Project and Price of CO_2

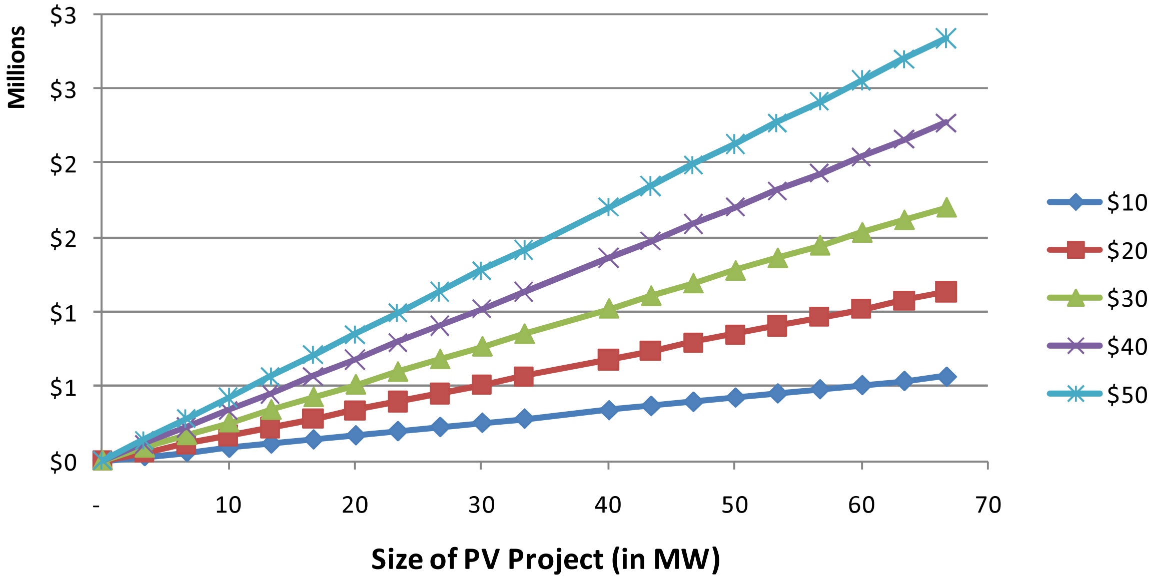
Price of CO_2 (in $/short ton)



MWh/Year	$5	$10	$15	$20	$25	$30	$35	$40	$45	$50	$55	$60
0	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
5,000	$14,187.50	$28,375.00	$42,562.50	$56,750.00	$70,937.50	$85,125.00	$99,312.50	$113,500.00	$127,687.50	$141,875.00	$156,062.50	$170,250.00
10,000	$28,375.00	$56,750.00	$85,125.00	$113,500.00	$141,875.00	$170,250.00	$198,625.00	$227,000.00	$255,375.00	$283,750.00	$312,125.00	$340,500.00
15,000	$42,562.50	$85,125.00	$127,687.50	$170,250.00	$212,812.50	$255,375.00	$297,937.50	$340,500.00	$383,062.50	$425,625.00	$468,187.50	$510,750.00
20,000	$56,750.00	$113,500.00	$170,250.00	$227,000.00	$283,750.00	$340,500.00	$397,250.00	$454,000.00	$510,750.00	$567,500.00	$624,250.00	$681,000.00
25,000	$70,937.50	$141,875.00	$212,812.50	$283,750.00	$354,687.50	$425,625.00	$496,562.50	$567,500.00	$638,437.50	$709,375.00	$780,312.50	$851,250.00
30,000	$85,125.00	$170,250.00	$255,375.00	$340,500.00	$425,625.00	$510,750.00	$595,875.00	$681,000.00	$766,125.00	$851,250.00	$936,375.00	$1,021,500.00
35,000	$99,312.50	$198,625.00	$297,937.50	$397,250.00	$496,562.50	$595,875.00	$695,187.50	$794,500.00	$893,812.50	$993,125.00	$1,092,437.50	$1,191,750.00
40,000	$113,500.00	$227,000.00	$340,500.00	$454,000.00	$567,500.00	$681,000.00	$794,500.00	$908,000.00	$1,021,500.00	$1,135,000.00	$1,248,500.00	$1,362,000.00
45,000	$127,687.50	$255,375.00	$383,062.50	$510,750.00	$638,437.50	$766,125.00	$893,812.50	$1,021,500.00	$1,149,187.50	$1,276,875.00	$1,404,562.50	$1,532,250.00
50,000	$141,875.00	$283,750.00	$425,625.00	$567,500.00	$709,375.00	$851,250.00	$993,125.00	$1,135,000.00	$1,276,875.00	$1,418,750.00	$1,560,625.00	$1,702,500.00
60,000	$170,250.00	$340,500.00	$510,750.00	$681,000.00	$851,250.00	$1,021,500.00	$1,191,750.00	$1,362,000.00	$1,532,250.00	$1,702,500.00	$1,872,750.00	$2,043,000.00
65,000	$184,437.50	$368,875.00	$553,312.50	$737,750.00	$922,187.50	$1,106,625.00	$1,291,062.50	$1,475,500.00	$1,659,937.50	$1,844,375.00	$2,028,812.50	$2,213,250.00
70,000	$198,625.00	$397,250.00	$595,875.00	$794,500.00	$993,125.00	$1,191,750.00	$1,390,375.00	$1,589,000.00	$1,787,625.00	$1,986,250.00	$2,184,875.00	$2,383,500.00
75,000	$212,812.50	$425,625.00	$638,437.50	$851,250.00	$1,064,062.50	$1,276,875.00	$1,489,687.50	$1,702,500.00	$1,915,312.50	$2,128,125.00	$2,340,937.50	$2,553,750.00
80,000	$227,000.00	$454,000.00	$681,000.00	$908,000.00	$1,135,000.00	$1,362,000.00	$1,589,000.00	$1,816,000.00	$2,043,000.00	$2,270,000.00	$2,497,000.00	$2,724,000.00
85,000	$241,187.50	$482,375.00	$723,562.50	$964,750.00	$1,205,937.50	$1,447,125.00	$1,688,312.50	$1,929,500.00	$2,170,687.50	$2,411,875.00	$2,653,062.50	$2,894,250.00
90,000	$255,375.00	$510,750.00	$766,125.00	$1,021,500.00	$1,276,875.00	$1,532,250.00	$1,787,625.00	$2,043,000.00	$2,298,375.00	$2,553,750.00	$2,809,125.00	$3,064,500.00
95,000	$269,562.50	$539,125.00	$808,687.50	$1,078,250.00	$1,347,812.50	$1,617,375.00	$1,886,937.50	$2,156,500.00	$2,426,062.50	$2,695,625.00	$2,965,187.50	$3,234,750.00
100,000	$283,750.00	$567,500.00	$851,250.00	$1,135,000.00	$1,418,750.00	$1,702,500.00	$1,986,250.00	$2,270,000.00	$2,553,750.00	$2,837,500.00	$3,121,250.00	$3,405,000.00

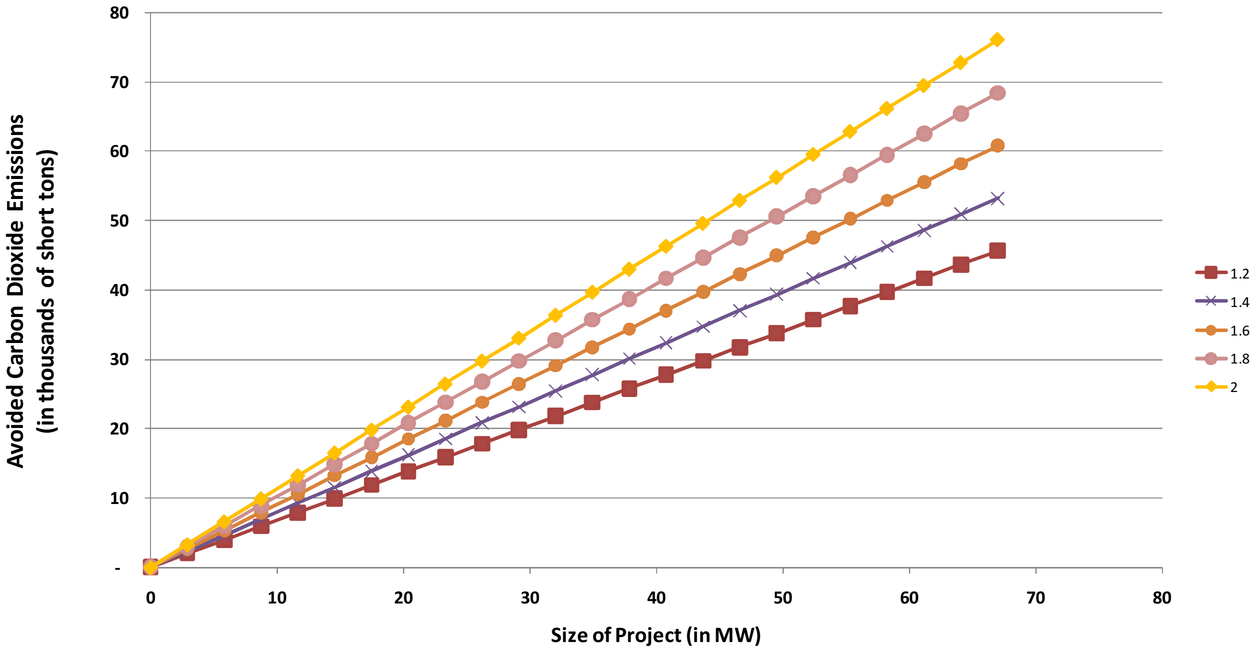
The cost savings associated with solar generation versus natural gas increase substantially as the size of the project increases. Assuming an emissions price of over $20/short ton, a large 67 MW nameplate capacity project (roughly 100,000 MWh/year in generation) would represent over $1,000,000 in annual savings from not having to purchase emission allowances. Figure 28 below, also shows how the cost savings associated with avoided carbon emissions offset purchases changes with the expected price of carbon. Even when looking at a smaller project, a 20MW (roughly 30,000 MWh/year in generation) for example, could save nearly $500,000 annually in carbon credit purchases.

Figure 28. Annual $ Savings from Avoided CO_2 Emissions by Project Size and by Price of CO_2 per ton



The savings outlined above are dependent on estimates for the overall electricity generation of the PV plant as well. Figure 29 demonstrates how the production factor of the system can affect the overall savings associated with emissions avoided. (Calculations used to generate Figure 30 assume a production factor of 1.5.)

Figure 29. Annual Carbon Emissions Avoided by Project Size and by Production Factor



An additional consideration that is not addressed fully in this report is the price volatility risk of natural gas and how uncertainty over variable costs could affect a natural gas plant's operations. For a more detailed discussion regarding historic price volatility of natural gas refer to Appendix C.

Chapter 3: NO_X Emissions

NO_X are produced during combustion of nitrogen rich fuels (e.g., fossil fuels) at high temperatures. Under the Clean Air Act, power generating facilities are required to monitor and control NO_X emissions, as these emissions pose significant environmental and health risks. NO_X compounds are air pollutants in their own right, but nitrogen also reacts with oxygen in the atmosphere to form ozone, which creates smog at the earth's surface. NO_X compounds also react with water to produce nitric acid, a major component of acid rain.

In addition to environmental and health concerns, there are financial incentives to limit NO_X emissions. NO_X emissions are regulated using a cap and trade system. Under this system, power facilities that can abate emissions at a low cost can sell their extra allowances on an open market.

NO_X Background

NO_X refers to the family of chemical compounds known as nitrogen oxides. Nitrogen is harmless in its inert state (N_2); it comprises the vast majority of the air that we breathe. When nitrogen reacts with oxygen and hydrogen, however, it forms compounds that are harmful to the environment and to human health. Figure 30 below lists the compounds found in the NO_X family.

Figure 30. Nitrogen Oxides

Formula	Name	Properties
N_2O	Nitrous oxide	Colorless gas Water soluble
NO **N_2O_2**	Nitric oxide Dinitrogen dioxide	Colorless gas Slightly water soluble
N_2O_3	Dinitrogen trioxide	Black solid Water soluble, decomposes in water
NO_2 **N_2O_4**	Nitrogen dioxide Dinitrogen tetroxide	Red-brown gas Very water soluble, decomposes in water
N_2O_5	Dinitrogen pentoxide	White solid Very water soluble, decomposes in water

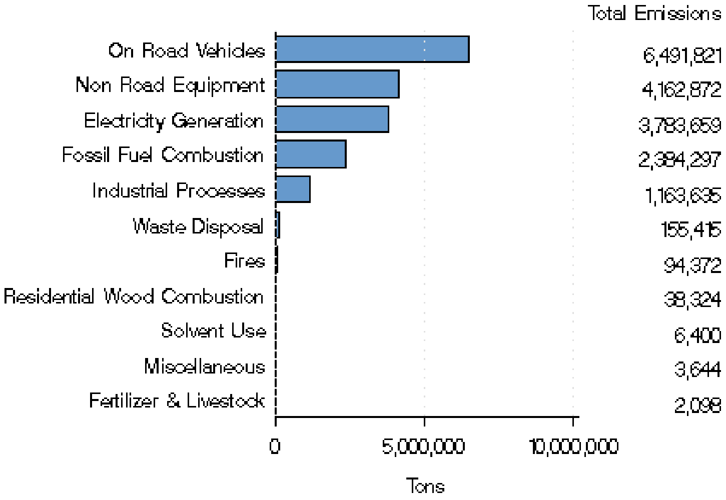
(U.S. EPA, 1999a)

Sources of NO_X

The primary source of anthropogenic NO_X is internal combustion engines in automobiles. Mobile sources emit approximately 50 percent of all NO_X in the U.S. Electric power plants; heavy manufacturing and other stationary sources contribute approximately 20 percent of NO_X emissions. The remaining 30 percent comes from other sources such as fires and decomposition of organic material (see Figure 31)

(U.S. EPA, 2009g). The scope of this paper will limit the discussion to NO_X emitted from electric power plants.

Figure 31. National NO_X Emissions by Source Sector



(U.S. EPA, 2009g)

Formation of NO_X

NO_X emissions are by-products of fuel combustion at electric power plants. They are formed when nitrogen combines with oxygen at high temperatures through one of the three mechanisms described below:

- *Thermal NO_X*: formed when nitrogen present in the air used in the firing process reacts with oxygen (present at the time of combustion) at temperatures greater than 1300 degrees C.
- *Fuel NO_X*: formed when the nitrogen present in fossil fuels (e.g., coal) oxidizes at temperatures greater than 750 degrees C. The amount of NO_X emitted is a function of the amount of nitrogen in the fuel source used at the plant.
- *Prompt NO_X*: formed when atmospheric nitrogen reactions with oxygen during the ignition portion of a coal fired flame. (IEA, 2006)

Thermal NO_X is the primary mechanism of NO_X formation at a natural gas power plant. The temperatures at which combustion occurs at natural gas plants are conducive to thermal NO_X production. The oxygen concentration, temperature, and time of exposure to the high temperature determine the exact amount of NO_X produced at the natural gas plant. One way to minimize NO_X emissions is to minimize excess oxygen in ambient air in the combustion chamber (to <1 percent) and to keep temperatures above 1475 degrees C. Prompt NO_X forms at a natural gas power plant, but at levels that are insignificant when compared to thermal NO_X. The formation of fuel NO_X is also negligible due to the low concentration of nitrogen in natural gas (U.S. EPA, 1998).

The majority of NO_X emitted from coal fired power plants are in the form of nitric oxide (NO) (IEA, 2006), which is created in the series of reactions listed below.

$$O + N_2 \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$N + OH \rightarrow NO + H$$

(Bowman, 1992)

NO is an unstable compound. When NO reacts with oxygen in the atmosphere, nitrogen dioxide (NO_2) is formed in the reaction below:

$$NO + HO_2 \rightarrow NO_2 + OH$$

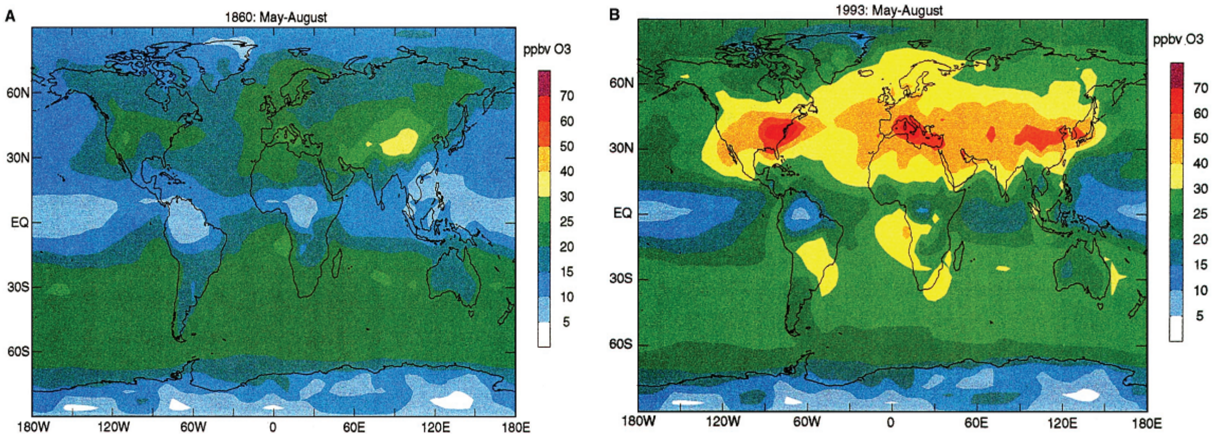
(Bowman, 1992)

NO and NO_2 are air pollutants in their own right, but they also react with oxygen in the atmosphere to form ozone, which is harmful to humans and plants in the lower atmosphere, and with water to produce nitric acid, a major component of acid rain. The formation and environmental effects of ozone and acid rain are discussed in the following sections.

Ozone

Ozone (O_3) is present in both the upper and lower atmosphere of the earth. Stratospheric ozone, found 20 to 60 kilometers above the earth's surface, provides a barrier for the sun's potentially harmful radiation (Sillman, 2009). Ozone also occurs naturally near the earth's surface, or troposphere, at levels between 10 and 20 parts per billion (ppb). Since the industrial revolution, however, anthropogenic sources of ozone have increased significantly (Akimoto, 2003) (see Figure 32 below).

Figure 32. Atmospheric Smog Concentrations: 1860 and 1993

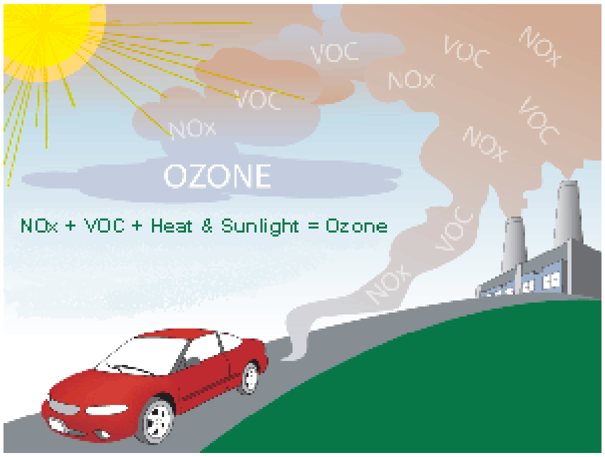


(Akimoto, 2003)

Since the industrial revolution, emissions from electric power generators, industrial facilities, motor vehicle exhaust, gasoline vapors, and chemical solvents have increased the levels of NO_X and volatile organic compounds (VOCs) in the troposphere. Ambient air in the preindustrial era contained about 10 to 15 ppb of ozone. Today, concentrations in warm seasons can reach 125 ppb when the temperature is hot and air flow minimal (Allen, 2002).

Tropospheric ozone is also called ground level ozone. In the presence of heat and sunlight, NO_X and VOCs react to form ground level ozone (U.S. EPA, 2010b). (See Figure 33 below, note- RO_2 refers to a chain of organic compounds with O_2 attached).

Figure 33. Formation of Ozone



$$\mathrm{VOC + OH \xrightarrow{[O_2]} RO_2 + H_2O}$$

$$\mathrm{CO + OH \xrightarrow{[O_2]} HO_2 + CO_2}$$

$$\mathrm{RO_2 + NO \xrightarrow{[O_2]} secondary\ VOC + HO_2 + NO_2}$$

$$\mathrm{HO_2 + NO \rightarrow OH + NO_2}$$

$$\mathrm{NO_2 + h\nu \rightarrow NO + O}$$

$$\mathrm{O + O_2 + M \rightarrow O_3 + M}$$

(U.S. EPA, 2010b) (Sillman, 2009)

Notice that the reactions that form ozone in Figure 33 can be cyclical. Most NO_X compounds have a lifetime of a few days. The cyclical nature of ozone further extends the life of NO_X compounds. NO_X is therefore capable of traveling long distances (depending on the weather and wind patterns) before creating ozone (U.S. EPA, 2010b).

Tropospheric ozone can damage the leaves of plants and trees, reducing forest growth and crop yields. It can also impair sensitive plants by making it difficult for them to produce and store food (U.S. EPA, 2008c). Ozone is also the primary component of smog, which can be detrimental to human health. The health effects of ground level ozone are discussed in Chapter 4 of this paper.

Acid Rain

NO_2 can react with water in the atmosphere to form nitric acid (HNO_3) (see the reactions below), a primary component of acid rain.

$$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$$

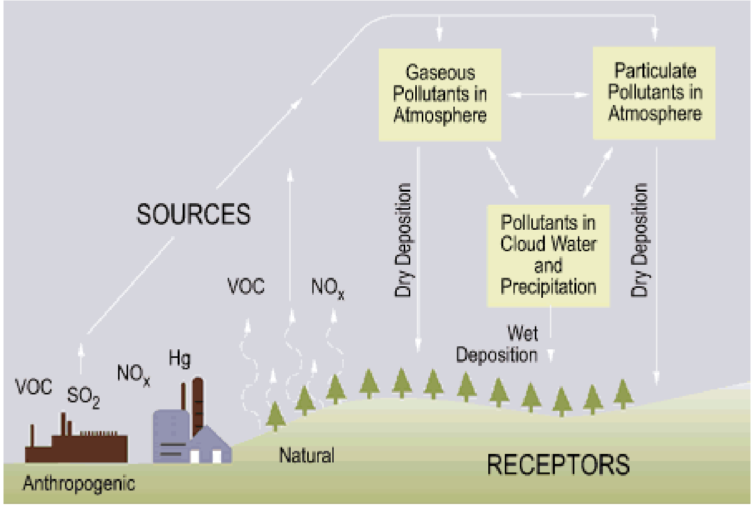
$$RO_2 + HO_2 \rightarrow ROOH + O_2$$

$$OH + NO_2 \rightarrow HNO_3$$

(Sillman, 2009)

Acid rain is the general term used for materials deposited from the atmosphere that contain elevated concentrations of NO_X and sulfur dioxide (SO_2). NO_X and SO_2 can come from either natural or anthropogenic sources, such as electric power generation. The EPA estimates that two-thirds of SO_2 and one quarter of NO_X come from fossil fuel combustion at electric power plants. If NO_X and SO_2 come in contact with moisture they react to form a mild solution of sulfuric and nitric acid that can fall to the ground as rain, snow, fog, or mist. This is called wet deposition. Dry deposition refers to NO_X and SO_2 that are incorporated into dust or smoke that then falls onto the ground, buildings, or trees (see Figure 34). Acid rain affects many parts of an ecosystem, as discussed in the sections below (U.S. EPA, 2007b).

Figure 34. Formation of Acid Rain



(U.S. EPA, 2007b)

Forests

Acid rain is not thought to be directly lethal to trees; it can be lethal to entire forests, however. Acid rain can limit nutrient absorption by dissolving nutrients and washing them out of the ecosystem. Soil with a lower pH also releases aluminum into the water, which is toxic to trees and other plant and animal life. When exposed to acid rain, leaves and needles of trees are stripped of their nutrients, making them more susceptible to other factors such as disease and cold (U.S. EPA, 2007b).

Surface Water

Acid rain that falls in the form of rain or snow directly affects aquatic habitats and ecosystems. An unpolluted stream, river, or lake generally has a pH of between 6 and 8. When the soils surrounding the aquatic ecosystem lose the ability to buffer, or neutralize, acidic compounds, the water becomes acidic (lower pH). Some polluted lakes have pH levels of below 5, the acidity of black coffee. Acidic soils also lose the ability to retain aluminum and instead release it into the water. Aluminum is extremely toxic to many aquatic species. The combination of low pH and high aluminum concentrations lead to higher stress and lower body weight and strength for fish and other organisms living in the water, which they need for reproduction and therefore species survival (sensitivity to acidity and aluminum concentrations vary by species) (U.S. EPA, 2007b).

Other effects

While the sensitive natural ecosystems feel the most harm from acid rain in the U.S. (especially in the Midwest and Northeast which are downwind from many coal fired power plants), acid rain has additional impacts. Paint on cars, trucks and other automobiles can be damaged through deposition and evaporation of acid rain. Deterioration of stone and concrete due to contact with acid rain reduces the quality, stability, and value of buildings, homes and natural rock formations. Acid rain also promotes faster deterioration of metals (U.S. EPA, 1999a).

Eutrophication

Acid rain increases the concentration of nitrogen in the soil. When the soil is unable to absorb additional nitrogen, the nitrogen begins to seep into surface and groundwater sources. Nitrogen is often a limiting nutrient for plant growth in both marine and freshwater ecosystems. Nitrogen runoff from the soil increases the amount of nutrients in aquatic systems and can increase plant growth, particularly algae and phytoplankton. A rapid increase of algae, often called an algal bloom or eutrophication, can harm an aquatic ecosystem. Algal growth blocks sunlight and requires oxygen. Rapid consumption of oxygen by algae often leads to oxygen depletion (hypoxia). Hypoxic aquatic systems lack enough oxygen to sustain most animal life. A “dead zone,” an aquatic area devoid of plant and animal life (such as that found at the mouth of the Mississippi River in the Gulf of Mexico), is a result of hypoxic conditions (U.S. EPA, 1999a).

Regulating NO_X Emissions

Congress passed the Clean Air Act Amendments in 1990 to protect and improve air quality. The Amendments require EPA to set National Ambient Air Quality Standards (NAAQS) for NO_X and other criteria pollutants and gives EPA the authority to monitor and control NO_X emissions (U.S. EPA, 2010c). EPA regulates NO_X emissions from electric generating sources through a cap and trade program, described below.

The Acid Rain Program

The Clean Air Act Amendments of 1990 created the Acid Rain Program, a market-based initiative used to reduce atmospheric levels of SO_2 and NO_X. The program targets large combustion facilities, primarily electric generating facilities, and operates like a cap and trade system.

Under the Acid Rain Program, EPA sets a ‘cap,’ or limit, on the collective level of NO_X emissions in the country and allots each combustion facility a certain number of emissions. Various mechanisms developed through multiple programs over the past twenty years have incorporated an increasing number of states; 27 states are currently under jurisdiction of the EPA for NO_X emissions. Generators can then ‘trade’ (buy or sell) these emissions permits on an exchange. Each NO_X emitter can therefore decide whether to abate or to purchase emissions allowances. Theoretically, those generators with a low cost of abatement will reduce emissions to the cost effective level and sell permits on the exchange; while those generators with high costs of abatement will purchase allowances in the market. This allows for the most cost efficient allocation of abatement (U.S. EPA, 2009h).

Methods of Abatement

Since the passage of the Clean Air Act, most new power plants have incorporated NO_X reducing technologies at the design and construction phase. Power plants that were in existence before the Clean Air Act have had to make modifications through retrofits to comply with the law.

As discussed above, NO_X is formed when nitrogen reacts with oxygen at high temperatures. Methods currently used to minimize NO_X emissions include:

- *Reduce peak temperature* – reducing the combustion temperature at the power plant alters the ratios of nitrogen and oxygen and reduces the amount of thermal NO_X produced.
- *Reduce time of exposure to high temperatures* – reducing the amount of time that nitrogen and oxygen are exposed to high combustion temperatures reduces the amount of nitrogen converted to NO_X.
- *Chemical reduction* – adding chemicals such as ammonia to the exhaust gas at the power plant removes oxygen from NO_X , essentially converting the NO_X back into nitrogen gas and water.
- *Oxidation of* NO_X – adding a catalyst such as hydrogen peroxide to combustion gases increases the solubility of NO_X and form nitric acid. Power plants can sell the nitric acid to customers or can neutralize the nitric acid to form calcium or ammonium salt, which can also be sold to customers. Plants that use this method must install scrubbers to prevent the release of N_2O_5, a byproduct of the oxidation reaction, into the atmosphere.
- *Removing nitrogen from combustion* – reducing the amount of nitrogen available to reaction with oxygen during combustion reducing the amount of NO_X produced at the plant. Plants can either use pure oxygen instead of outside air (which is approximately 80 percent nitrogen) during combustion or can use a fuel source with low nitrogen content.
- *Adsorption and absorption* – adding sorbents (ammonia, powdered limestone, aluminum oxide, or carbon) to flue gas at the power plants removes NO_X molecules in the gas.

Often, a combination of the above methods will be employed at the power plant to reduce concentrations of NO_X (U.S. EPA, 1999a). Natural gas does not contain a lot of nitrogen. As a result, natural gas power plants typically reduce combustion temperature and/or time of exposure to reduce NO_X emissions (U.S. EPA, 1998).

There are many technologies available to reduce NO_X emissions using the abatement methodologies described above. Each technology varies in cost, effectiveness, applicability, and side effects. See Appendix D for a description of NO_X limiting technologies and the associated impacts. Thus, the type and process of abatement is left up to each particular source of NO_X.

Costs of abatement technologies continue to fall as competition increases and technologies are becoming better understood and more widely available. According to the EPA, the costs for abatement in natural gas turbines is estimated to be $32.4 pet kW (1997 dollars), with annual operating costs of $0.49 per kW and can range in effectiveness of NO_X removal from 40 to 50 percent. See Appendix E for cost estimates for various abatement technologies.

Monitoring, Reporting, and Verification

EPA strictly enforces its NO_X monitoring requirements. EPA requires electric generating facilities to continuously monitor NO_X mass emissions (measured in lbs/mmBtu) and heat unit input (measured in mmBtu/hr). Emitters multiply these two measurements to calculate NO_X emissions in lbs/hr and then report these emissions to EPA. EPA requires some states to submit emissions monitoring results every quarter and requires other states to only submit monitoring results for the second and third quarters (ozone season) (U.S. EPA, 2010h).

Evolution of the NO_X Market

EPA created the *Ozone Transport Commission (OTC) NO_X Budget Program* in 1999 to help states reach the NAAQS for ground level ozone and to reduce summertime NO_X emissions in the northeastern U.S. The OTC Budget Program affected 11 northeastern states[14] and the District of Columbia and lasted until 2002. The program limited NO_X emissions from May 1 through September 30 – the time of year when ozone formation is the highest. Collective emissions of NO_X from large electricity generators in each of these states could not exceed 219,000 tons per year (compared to the baseline level of emissions was 490,000 tons per year in 1990) (U.S. EPA, 2009i).

EPA replaced the OTC NO_X Budget Program with the *NO_X State Implementation Plan (SIP)* in 2003. The central focus of the SIP program was to mitigate the transportation of NO_X. The EPA issued a standard of .08 ppm over an 8 hour period affecting 19 states[15] and the District of Columbia (see Figure 35 below).

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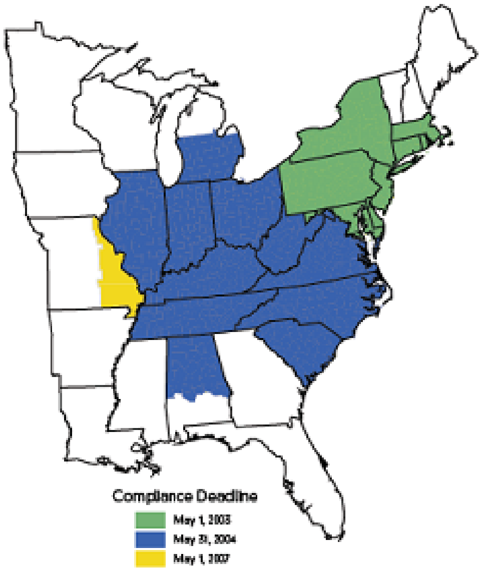
[14] States affected: CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT

[15] States affected: AL, CT, DE, IL, IN, KY, MA, MD, MI, NC, NJ, NY, OH, PA, RI, SC, TN, VA, WV.

Figure 35. States Included in the SIP Program

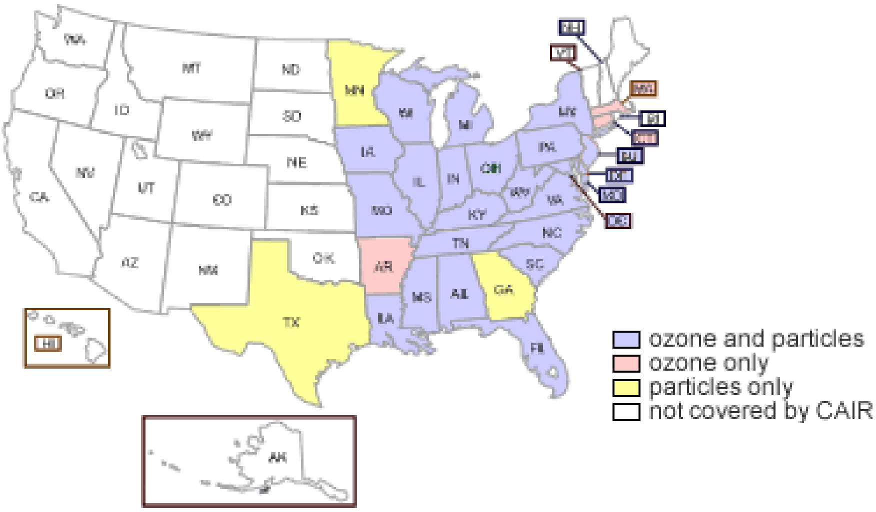


(U.S. EPA, 2003)

EPA administered the program but allowed each state to develop its own plan for reducing emissions. The program also allowed states to trade allowances in an effort to efficiently allocate resources across participating states. This trading program was in effect during the summer months. In 2008 EPA strengthened the emissions standard to .075 ppm over an 8 hour period (U.S. EPA, 2009h).

EPA issued the Clean Air Interstate Rule (CAIR) in March of 2005. CAIR affected 28 eastern states (see Figure 36) and the District of Columbia and established three separate trading programs to help states achieve NAAQS – an annual NO_X program, a seasonal NO_X program, and an annual SO_2 program.

Figure 36. States Affected by CAIR



(U.S. EPA, 2010d)

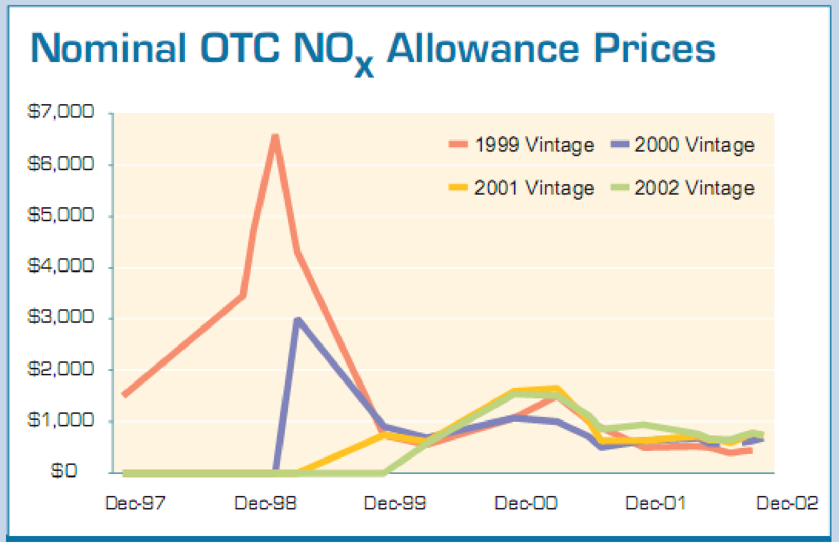
CAIR is similar to the SIP Program, but gives states the flexibility to develop their own strategies to reduce NO_X emissions. Under CAIR, states can participate in the cap and trade market administered by EPA or they can achieve emissions reductions through "measures of the state's own choosing" (U.S. EPA, 2009h).

In July 2008, the DC District Court of Appeals issued a statement remanding CAIR, declaring it illegal. EPA proposed the Transport Rule in July 2010 to replace CAIR. If finalized, the Transport Rule would reduce SO_X and NO_X emissions (to 71 percent and 52 percent, respectively) and expand the SIP program to include 31 states and the District of Columbia. The aim of the program is to reduce NO_X and SO_X from power plants whose emissions cross state borders. One of the options for reducing emissions in the Transport Rule includes emissions trading (U.S. EPA, 2010h).

Price Signals in the Cap and Trade Market

As discussed above, EPA administered three separate and successive NO_X trading schemes since the passage of the Clean Air Act. The early stage of trading programs is generally characterized by high, volatile allowance prices. But, as participants learn more about compliance methods and market prices, both volatility and prices typically decline. Figure 37 shows the prices of NO_X OTC trading program during the early period of the program. At the beginning of the trading market in (1997 to 1998) prices spiked to nearly $7,000 per ton. As the market matured and more players entered, prices settled around $1,000 per ton.

Figure 37. Historical NO_X Prices



(Hart, 2009b)

The SIP exhibited price trends similar to the OTC. Early permit trading was volatile and expensive, but prices settled between $500 and $1,000 per ton in 2007 (see Figure 38 below).

Figure 38. Recent Spot Prices for NO$_X$

(Hart, 2009b)

If EPA promulgates the Transport Rule and if the rule includes a trading scheme for NO$_X$, it is likely that the trading program will also have an initial period of price volatility until participants gain a better understanding of market prices and abatement possibilities (Hart, 2009a).

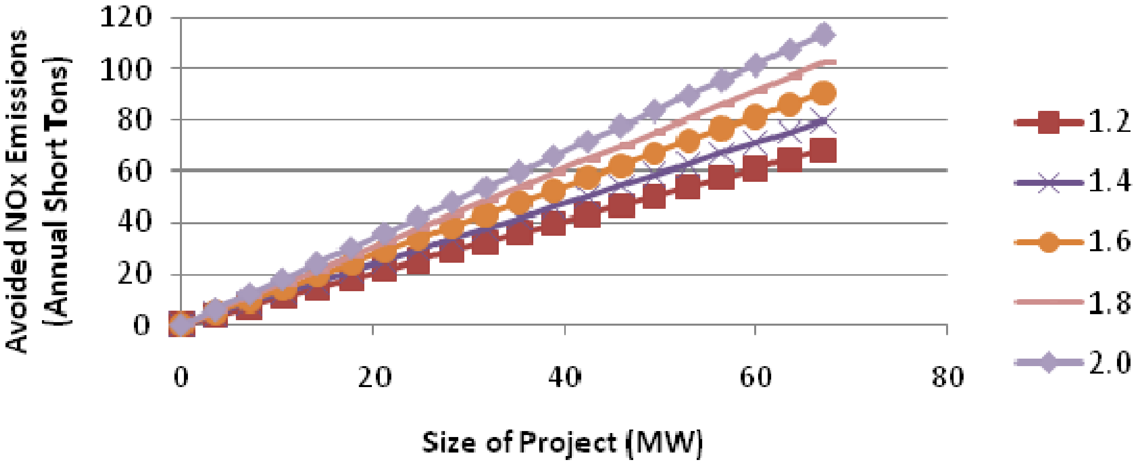
Figure 39 below depicts the average NO$_X$ emissions avoided by sourcing electricity from a PV facility as opposed to the average grid electricity.

Figure 39. Avoided NO$_X$ Emissions by Size of Polar Project

Size of Solar Project (MW)	MWh/yr	Annual Avoided Emissions (in short tons)
-	0	-
3	5,000	4.25
7	10,000	8.50
10	15,000	12.75
13	20,000	17.00
17	25,000	21.25
20	30,000	25.50
23	35,000	29.75
27	40,000	34.00
30	45,000	38.25
33	50,000	42.50
40	60,000	51.00
43	65,000	55.25
47	70,000	59.50
50	75,000	63.75
53	80,000	68.00
57	85,000	72.25
60	90,000	76.50
63	95,000	80.75
67	100,000	85.00

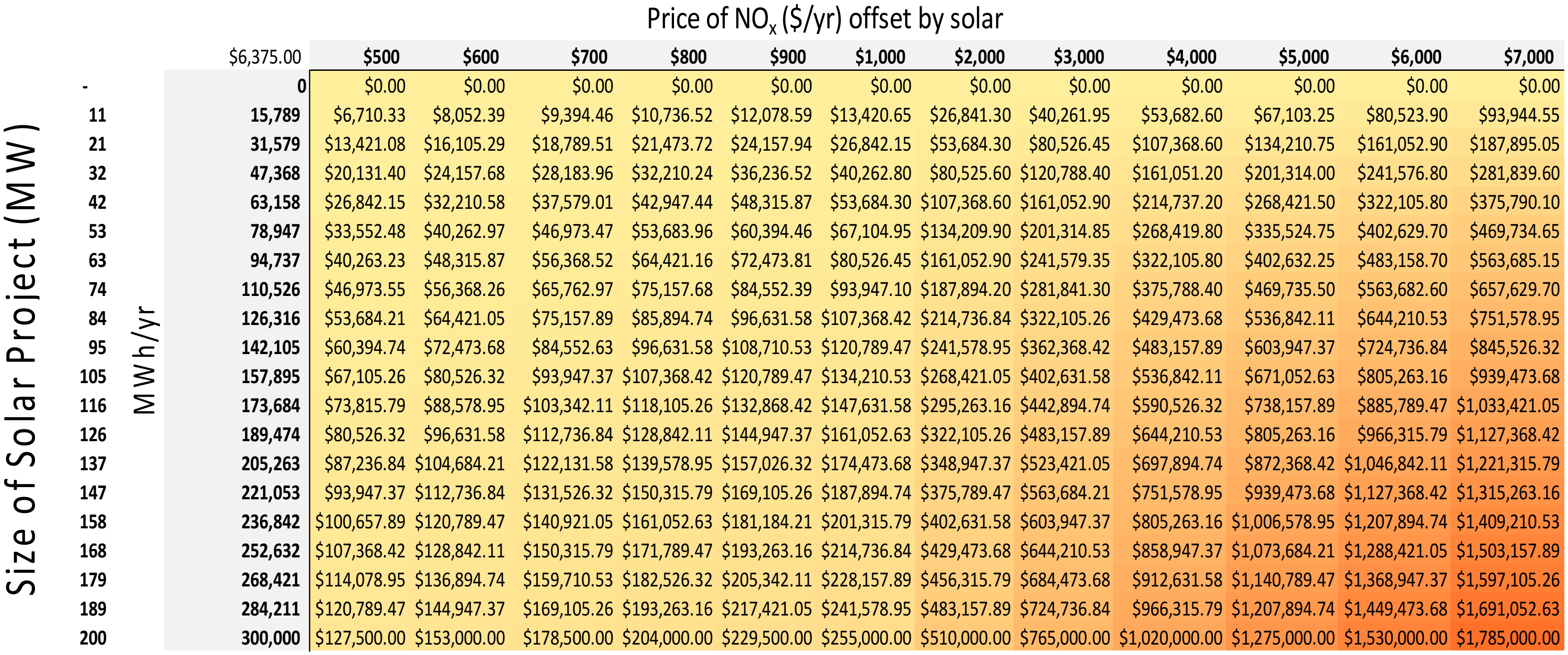
The total NO_X emissions avoided by the PV plant varies linearly with the size of the plant. Figure 40 below shows this relationship over a range of production factors.

Figure 40. Annual NO_X Emissions Avoided by Project Size and by Production Factor



The sensitivity analysis in Figure 41 below shows the cost to natural gas power plants due to NO_X emissions based on the size of the plant (in MWh/yr) and cost of allowances (in \$/ton). Since a PV power plant does not emit NO_X, it is assumed that the direct cost benefit of a PV plant compared with a natural gas plant can be the total cost of NO_X emissions per year.

Figure 41. Cost Savings by Size of PV Project and Price of NO_X[16]



Price of NO_x ($/yr) offset by solar

Size of Solar Project (MW)	MWh/yr $6,375.00	$500	$600	$700	$800	$900	$1,000	$2,000	$3,000	$4,000	$5,000	$6,000	$7,000
-	0	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
11	15,789	$6,710.33	$8,052.39	$9,394.46	$10,736.52	$12,078.59	$13,420.65	$26,841.30	$40,261.95	$53,682.60	$67,103.25	$80,523.90	$93,944.55
21	31,579	$13,421.08	$16,105.29	$18,789.51	$21,473.72	$24,157.94	$26,842.15	$53,684.30	$80,526.45	$107,368.60	$134,210.75	$161,052.90	$187,895.05
32	47,368	$20,131.40	$24,157.68	$28,183.96	$32,210.24	$36,236.52	$40,262.80	$80,525.60	$120,788.40	$161,051.20	$201,314.00	$241,576.80	$281,839.60
42	63,158	$26,842.15	$32,210.58	$37,579.01	$42,947.44	$48,315.87	$53,684.30	$107,368.60	$161,052.90	$214,737.20	$268,421.50	$322,105.80	$375,790.10
53	78,947	$33,552.48	$40,262.97	$46,973.47	$53,683.96	$60,394.46	$67,104.95	$134,209.90	$201,314.85	$268,419.80	$335,524.75	$402,629.70	$469,734.65
63	94,737	$40,263.23	$48,315.87	$56,368.52	$64,421.16	$72,473.81	$80,526.45	$161,052.90	$241,579.35	$322,105.80	$402,632.25	$483,158.70	$563,685.15
74	110,526	$46,973.55	$56,368.26	$65,762.97	$75,157.68	$84,552.39	$93,947.10	$187,894.20	$281,841.30	$375,788.40	$469,735.50	$563,682.60	$657,629.70
84	126,316	$53,684.21	$64,421.05	$75,157.89	$85,894.74	$96,631.58	$107,368.42	$214,736.84	$322,105.26	$429,473.68	$536,842.11	$644,210.53	$751,578.95
95	142,105	$60,394.74	$72,473.68	$84,552.63	$96,631.58	$108,710.53	$120,789.47	$241,578.95	$362,368.42	$483,157.89	$603,947.37	$724,736.84	$845,526.32
105	157,895	$67,105.26	$80,526.32	$93,947.37	$107,368.42	$120,789.47	$134,210.53	$268,421.05	$402,631.58	$536,842.11	$671,052.63	$805,263.16	$939,473.68
116	173,684	$73,815.79	$88,578.95	$103,342.11	$118,105.26	$132,868.42	$147,631.58	$295,263.16	$442,894.74	$590,526.32	$738,157.89	$885,789.47	$1,033,421.05
126	189,474	$80,526.32	$96,631.58	$112,736.84	$128,842.11	$144,947.37	$161,052.63	$322,105.26	$483,157.89	$644,210.53	$805,263.16	$966,315.79	$1,127,368.42
137	205,263	$87,236.84	$104,684.21	$122,131.58	$139,578.95	$157,026.32	$174,473.68	$348,947.37	$523,421.05	$697,894.74	$872,368.42	$1,046,842.11	$1,221,315.79
147	221,053	$93,947.37	$112,736.84	$131,526.32	$150,315.79	$169,105.26	$187,894.74	$375,789.47	$563,684.21	$751,578.95	$939,473.68	$1,127,368.42	$1,315,263.16
158	236,842	$100,657.89	$120,789.47	$140,921.05	$161,052.63	$181,184.21	$201,315.79	$402,631.58	$603,947.37	$805,263.16	$1,006,578.95	$1,207,894.74	$1,409,210.53
168	252,632	$107,368.42	$128,842.11	$150,315.79	$171,789.47	$193,263.16	$214,736.84	$429,473.68	$644,210.53	$858,947.37	$1,073,684.21	$1,288,421.05	$1,503,157.89
179	268,421	$114,078.95	$136,894.74	$159,710.53	$182,526.32	$205,342.11	$228,157.89	$456,315.79	$684,473.68	$912,631.58	$1,140,789.47	$1,368,947.37	$1,597,105.26
189	284,211	$120,789.47	$144,947.37	$169,105.26	$193,263.16	$217,421.05	$241,578.95	$483,157.89	$724,736.84	$966,315.79	$1,207,894.74	$1,449,473.68	$1,691,052.63
200	300,000	$127,500.00	$153,000.00	$178,500.00	$204,000.00	$229,500.00	$255,000.00	$510,000.00	$765,000.00	$1,020,000.00	$1,275,000.00	$1,530,000.00	$1,785,000.00

Costs Calculation: (xLbs/MWh of natural gas *(X MWh/ yr) * (1 ton/ 2000lbs) * $/ton = $/yr

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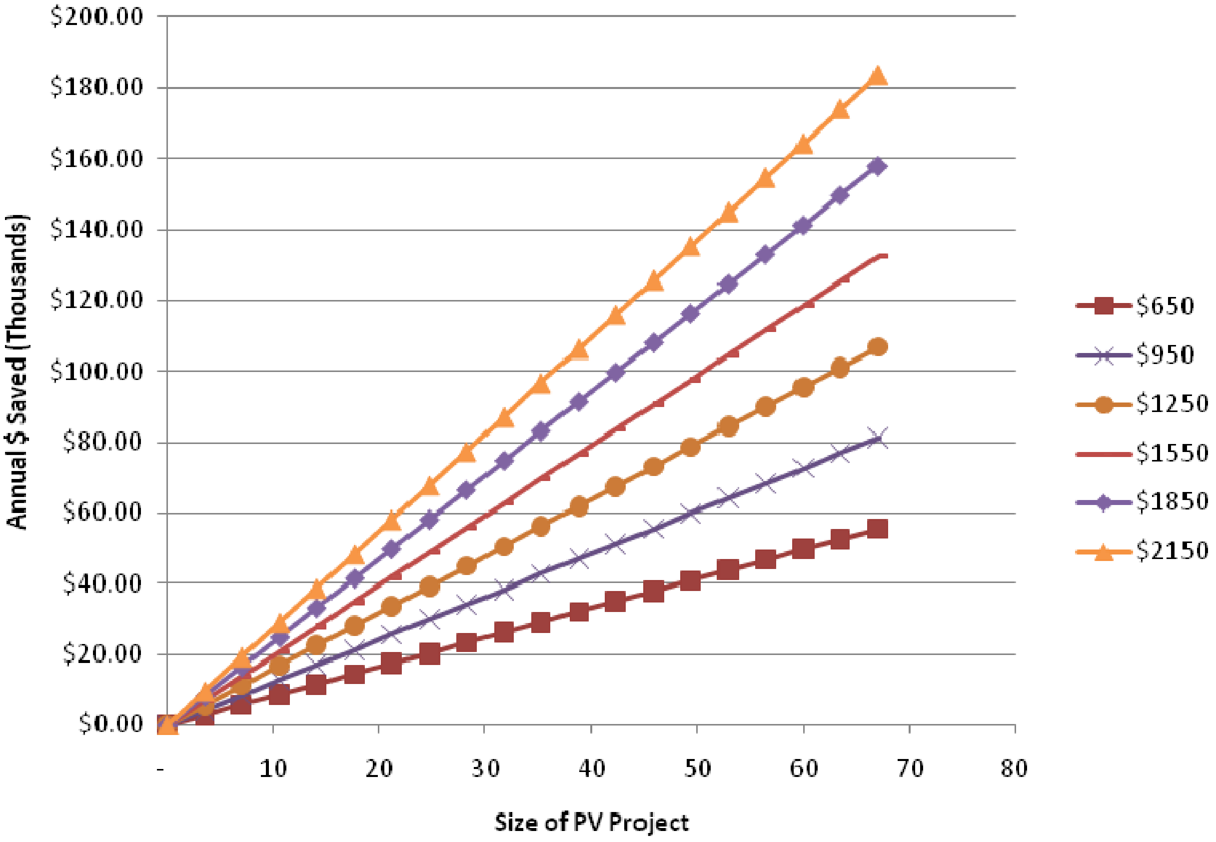
[16] The emissions factor used in this analysis is a national average for natural gas plants. This factor is not specific to a NGCC plant because reliable national averages for NGCC are not currently available.

Figure 41 shows the relationship between the cost per ton of NO_X and the size of a solar power plant. A 5 MW solar plant, for example, will save $5,368 per year at a price of $800 per ton of NO_X. These costs represent the money that would be spent on NO_X allowances on the open market. As to be expected, as the price of NO_X increases, or the size of the solar project increases, the solar project becomes more valuable in terms of offsetting NO_X emissions.

The annual savings total NO_X emissions avoided by the PV plant varies linearly with the size of the plant. Figure 42 below shows this relationship over a range of NO_X prices per ton.

Figure 42. Annual $ Savings from Avoided NO_X Emissions by Project Size and by Price of NO_X per ton



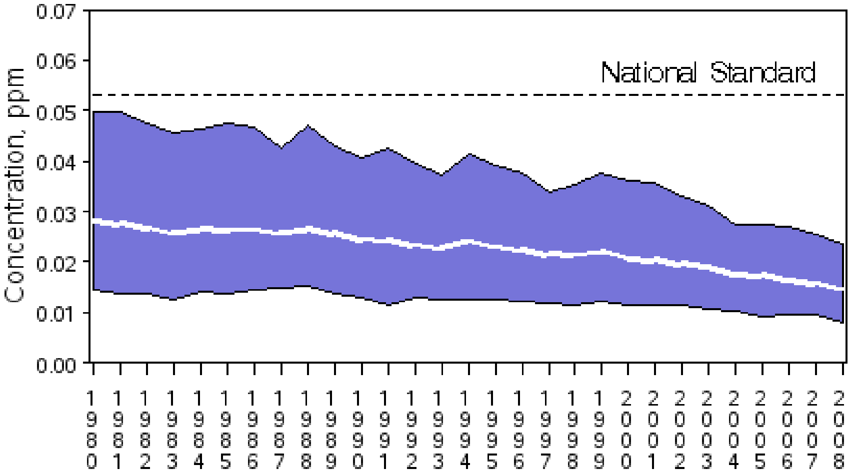
Results of NO_X Controls

One way to measure the effectiveness of NO_X controls is to look at NO_2 concentrations. NO_2 is the primary form of NO_X generated from anthropogenic sources and is used as an indicator for the larger family (primarily nitrous acid and nitric acid) due to its potency in the environment and the adverse human health effects it has on the respiratory system.

As shown in Figures 43 and 44 below, NO_2 concentrations (measured in ppm) decreased by 46 percent between 1980 and 2008, and by 35 percent between 1990 and 2008.

Figure 43. NO2 Air Quality, 1980 – 2008

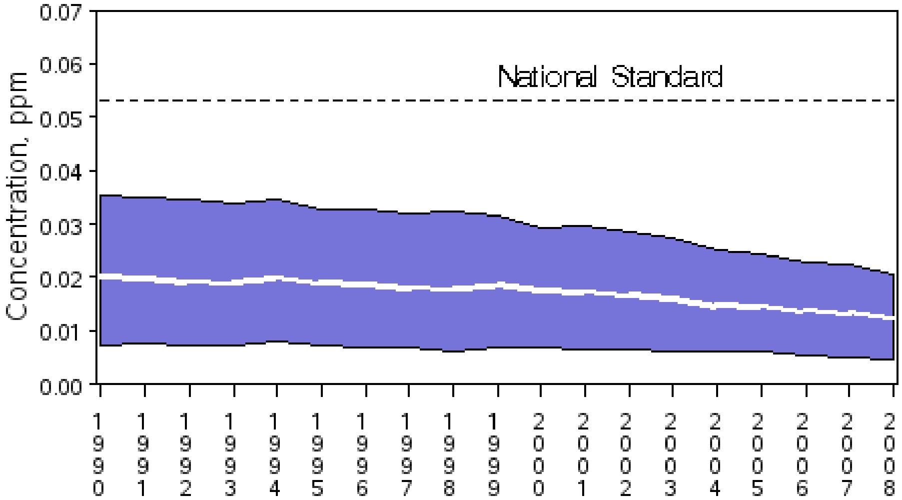
(National trend based on 75 sites and on annual arithmetic average)



(U.S. EPA, 2010a)

Figure 44. NO2 Air Quality, 1990 – 2008

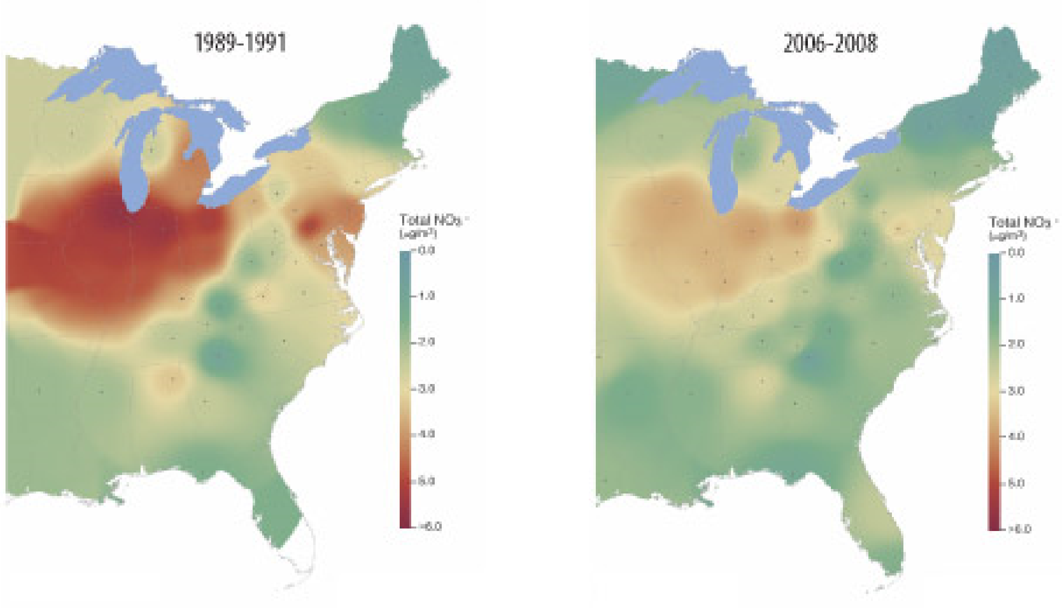
(National trend based on 151 sites and on annual arithmetic average)



(U.S. EPA, 2010a)

The figure below shows the change in total nitrate concentration from the period prior to the implementation of the Acid Rain Program (1989-91) and after implementation (2006-08). The red areas indicate high nitrate concentrations, and green indicates lower concentration. Nitrate concentrations decreased between the two time periods show in Figure 45, particularly in the Midwest and mid-Atlantic regions.

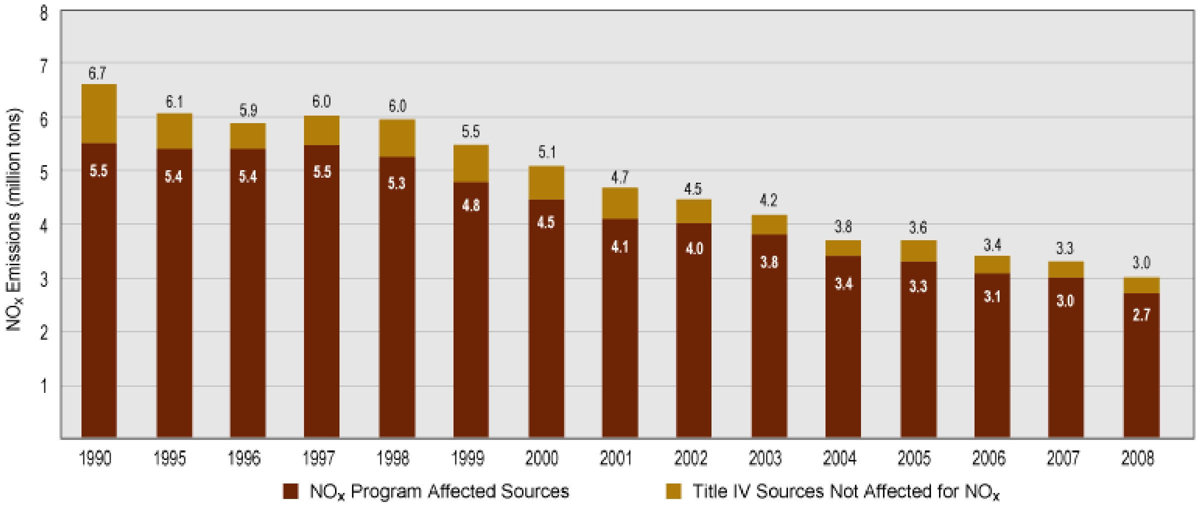
Figure 45. Annual Mean Ambient Total NO_2 Concentration, 1989-91 and 2006-08



(U.S. EPA, 2009b)

Figure 46 below shows the total NO_X emissions from all sources included in the NO_X Budget Program from 1990 to 2008. NO_X emissions from these sources fell from 5.5 to 2.7 million tons during this period.

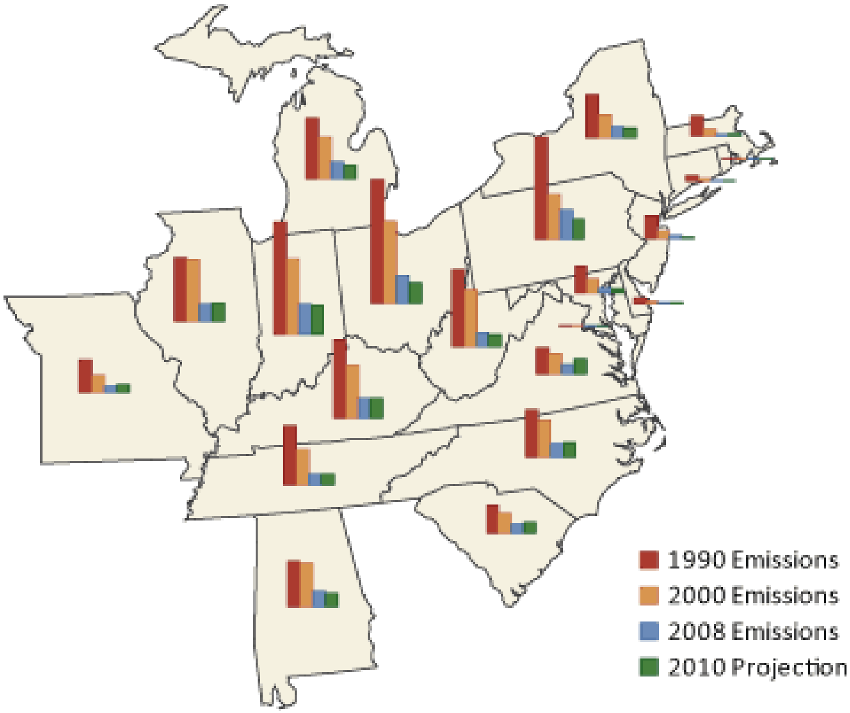
Figure 46. Historical NO_X Emissions from Sources Included in the Budget Program



(U.S. EPA, 2009b)

The Figure 47 below shows NO_X emissions for states that participate in the NO_X trading program. NO_X emissions declined between 1990 and 2008 in each state included in the figure.

Figure 47. State Level NO_X Emissions during Ozone Season



(U.S. EPA, 2009a)

Overall, NO_X emissions - and by proxy acid rain - and ground level ozone have declined since the implementation of the EPA's Acid Rain Program. The cap and trade model has also served as an example for other emissions markets, most notably Europe, which has instituted a cap and trade program for CO_2 emissions.

Chapter 4: Health Impacts of Natural Gas NO_X Emissions

Because solar PV emits only negligible amounts of pollutants throughout its lifecycle, it offers a significant public health benefit over fossil fuel generation, including natural gas-fired power. If all natural gas were pure methane (CH_4), its combustion in pure oxygen (O_2) would yield only two byproducts: CO_2 and water vapor. However, natural gas contains a small percentage of other molecules and reacts with molecules present in ambient air. Due to these factors, gas-fired power plants emit particulate carbon, carbon monoxide, and nitrogen oxides, in addition to CO_2, water vapor, and heat (U.S. EIA, 1998).

Research identifying positive correlations between increased illness and high concentrations of several air pollutants led to passage of the 1971 Clean Air Act (U.S. EPA, 2010g). The Clean Air Act called NO_X and ground-level ozone, particulate matter, carbon monoxide, sulfur oxides, and lead "criteria pollutants" because EPA must set permissible emission levels "by developing human health-based and/or environmentally-based criteria." The human health-based limits are called the primary standards for a criteria air pollutant, and the limits to prevent environmental and property damage are secondary standards (U.S. EPA, 2008a). Despite EPA standards, the American Lung Association estimated that in 2009, over 175 million Americans or about 58 percent of the population live in areas where air pollutant concentrations can reach dangerous levels (American Lung Association, 2010).

This report focuses on the health impacts of NO_X emissions. Gas-fired power produces 10 percent of national anthropogenic NO_X emissions (U.S. EIA, 1998). While particulate carbon and carbon monoxide (CO) have serious health impacts, natural gas combustion is not a significant source of direct emissions of CO or particulate matter. Public health impacts that may be associated with increased concentrations of CO_2 in the atmosphere are also outside the scope of this report because exact impacts are unknown and cannot be attributed to any particular source of greenhouse gas emissions.

NO_X Emissions

As discussed in Chapter 3, NO_X reacts with water and sunlight to form dangerous concentrations of ground-level ozone in the summer (U.S. EPA, 2010f). It also reacts with ammonia, moisture, and other particles in the atmosphere to form particulate matter in the form of nitrates. Particulate matter is "a mixture of solid particles and liquid droplets found in the air; fine particles ($PM_{2.5}$) are smaller than 2.5 microns (millionths of a meter) in diameter." Although power plants directly emit particles, "their major contribution to particulate matter air pollution is emissions of SO_2 and NO_X," which react to form sulfate and nitrate particles that constitute a large proportion of fine particulate matter pollution nationally (U.S. EPA, 2004).

Scientific studies have linked short-term exposures to elevated concentrations of NO_X—that is, exposures ranging from 30 minutes to 24 hours—with respiratory problems in both healthy and unhealthy individuals (U.S. EPA, 2004). While research has not firmly established a causal relationship between NO_X emissions and health effects, a sufficient body of research finds that reducing particulate matter improves public health (ABT Associates, Inc., 2004). Children, the elderly, individuals with existing respiratory problems, and frequent outdoor exercisers are more vulnerable than others to the effects of NO_X and its by-products. The health problems caused by NO_X emissions can be measured by increased hospital admissions and premature deaths, thus translating directly to public health costs.

NO_X-related compounds can be carried through the air for hundreds or thousands of miles and react with various compounds in transit, so the effects of emissions from one power plant may impact distant populations (Allen, 2002). To limit NO_X-related emissions, regulators mainly measure levels of NO_2, which indicate levels of other NO_X-related compounds like nitrous acid and nitric acid and precedes their formation (U.S. EPA, 2009e).

Studying Health Impacts of Air Pollutants

Epidemiological studies examine how pollutants impact the health of a population. Studies related to NO_X, ozone, and PM used data from air pollutant monitoring sites, hospital admissions broken out by symptoms, deaths, and population characteristics to infer impacts of human exposure to pollutants. Studies generally compare data collected during periods of normal concentrations of pollutants to data collected during episodes of higher-than-normal concentrations of pollutants over short or long periods of time. They examine the relationships between pollutant concentrations and hospital admissions and mortality statistics to determine correlations between high concentrations of certain pollutants and increased illness or mortality.

Regulators use correlations from epidemiological studies to estimate the health impacts of various limitations on NO_X emissions. In general, these studies have found that the concentration of NO_X and its derivatives has a greater effect on human health than the length of time of exposure (Gardner, 1980). For this reason, EPA’s standards include a maximum hourly NO_X concentration as well as a maximum annual concentration.

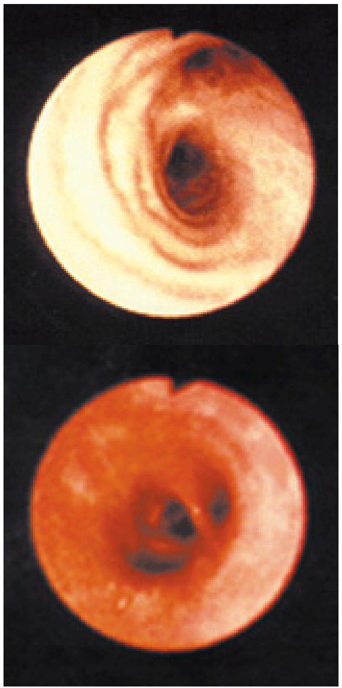
Health Impacts of Ozone

As discussed in Chapter 3, ground level concentrations of ozone in the U.S. have increased significantly since the Industrial Revolution. Elevated concentrations of ozone create smog and irritate human lungs, leading to respiratory inflammation (U.S. EPA, 2010f) (Allen, 2002).

Ozone breaks chemical bonds in the lining of human airways that reform in different ways, causing inflammation and reduced protection against airborne microbes, toxic chemicals, and allergens (Allen, 2002). Scientists compare this damage to premature aging of the lungs. Generally, exposure to high concentrations of ground-level ozone can cause or aggravate the following conditions:

- Decreases in lung function due to inflammation, resulting in difficulty breathing, shortness of breath, and other symptoms
- Respiratory symptoms, including bronchitis, aggravated coughing, and chest pain

- Increased incidence and/or severity of respiratory problems, including aggravation of asthma and higher risk of contracting respiratory illnesses such as pneumonia and bronchitis
- Chronic inflammation and irreversible structural changes in the lungs that, with repeated exposure, can lead to respiratory illness (U.S. EPA, 2004) (U.S. EPA, 2008c)



This photo shows a healthy lung air way (top) and an inflamed lung air way (bottom). Ozone can inflame the lung's lining, and repeated episodes of inflammation may cause permanent changes in the lung. (U.S. EPA, 1999b)

In healthy individuals, the symptoms from exposure to elevated concentrations of ozone are usually temporary and include inflammation and restricted breathing, coughing, shortness of breath, and pain when inhaling deeply. Individuals with lung disease, children, older adults, and athletes or other physically active individuals are at the highest risk for symptoms when ozone concentrations are high (U.S. EPA, 2008c). EPA estimates that 5 to 20 percent of the total U.S. population has an unexplained greater susceptibility to develop symptoms from ozone exposure (Allen, 2002).

For individuals with asthma, symptoms may persist and be much more dangerous. People with asthma may experience symptoms at lower ozone concentration levels than healthy people or react more acutely. The biggest danger is that an asthmatic's reaction to elevated ozone concentrations may worsen his or her asthma, leading to an asthma attack or requiring additional treatment (U.S. EPA, 2004).

Children are at greater risk than the general population because their lungs are not fully developed, their respiratory defenses are weaker, they breathe in more air per pound of body weight, and they tend to spend more time exercising outside than adults. Therefore, they generally take in more air pollution than adults and are more vulnerable to its effects. A study of fourth graders conducted by the University of Southern California's Keck School of Medicine found that each increase in ozone concentration of 20 ppb was associated with a 63 percent increase in the rate of school absences and an 83 percent increase in respiratory illness (Gilliland, 2001). 20 ppb represents a relatively small and common increase in ozone concentration (Allen, 2002).

Higher concentrations of ozone have been found to correspond to higher risk of respiratory symptoms in the elderly. Studies in Minneapolis-St. Paul, Birmingham, and Detroit found that the elderly had a higher relative risk of hospital admission due to pneumonia within a few days of an episode of high ozone measurements. The Birmingham and Detroit studies found that an increase of 50 ppb in the average daily ozone concentration was associated with hospital admissions for pneumonia among the elderly at 1.14 and 1.3 times respectively the average admission rate for the general population (Schwartz, 1994a) (Schwartz, 1994b). The Minneapolis-St. Paul study found that the elderly had a relative risk of 1.13 (Schwartz, 1994c).

Finally, athletes and individuals who frequently exercise outdoors are more vulnerable to increased ozone concentrations because they are more likely to be exposed to ozone and to breathe in more of it than the general population. The National Institute of Environmental Health Sciences found that volunteers exposed to 80 ppb of ozone above the level in ambient air experienced a 5 to 10 percent decrease in lung capacity after 6.5 hours of exposure while engaged in moderate exercise (NIEHS, 2001).

A few studies suggest that exposure to high ozone concentrations can cause disease. The Adventist Health (AHSMOG) study found a correlation between elevated short-term ozone exposures and asthma development. The study followed 3091 nonsmokers between the ages of 27 and 87 for 15 years. For males, AHSMOG, "observed a significant relationship between report of doctor diagnosis of asthma and 20 year mean 8-hour average ambient ozone concentration," but the study did not find the same relationship in females. The study's findings, "suggest that long-term exposure to ambient ozone is associated with development of asthma in adult males" (McDonnell et al., 1999).

From this same data, researchers found that ground-level ozone increased the risk of incident lung cancer in males by 3.56 percent for males exposed more frequently to ozone concentrations of 100 parts per billion. It did not find this relationship for females but states that gender differences in exposure may partially explain the difference between results in male and female subjects (Beeson, Abbey, & Knutsen, 1998). Ozone was also strongly associated with lung cancer mortality in male subjects. Males exposed more often to ozone concentrations above 100 parts per billion were 4.19 times more likely to die of lung cancer (Abbey et al., 1999).

Health Impacts of Particulate Matter

Fine particulate matter, $PM_{2.5}$, is one of the most controversial and potentially dangerous air pollutants for human health. Fine particles in the atmosphere are mainly generated by combustion and are emitted from motor vehicles, power generation, wood burning, and industrial facilities. In urban areas, fine particles are composed of sulfur and nitrogen oxide emissions and sulfates and nitrates derived from SO_x and NO_X, including some acidic particles (Pope C. , 2000). These particles are small enough to be inhaled and have been directly related to respiratory and heart problems.

PM is small enough to bypass first-line defenses like the nose and upper airways and lodge itself deep in human lungs (Rizzo, 2010). Scientists do not yet clearly understand how PM affects cardiac function, but some ultrafine (<0.1µm in diameter) PM is small enough to enter the blood stream from the lungs (Oberdorster, Oberdorster, & Oberdorster, 2005) and studies have linked specific cardiovascular conditions to increased PM concentrations (Pope & Dockery, 2006). Because fine particles can penetrate indoor settings, there is little difference between indoor and outdoor concentrations and therefore exposures (Dockery & Spengler, 1981). In general, exposure to high concentrations of fine particles can cause the following symptoms or conditions:

- Increased incidence of premature death, primarily in the elderly and those with heart or lung disease;
- Aggravation of respiratory or cardiovascular illness in children and individuals with heart or lung disease
- Increased work loss days, school absences, and emergency room visits
- New cases of chronic bronchitis
- Decreased lung function and symptomatic effects, including acute bronchitis, particularly in children and asthmatics (U.S. EPA, 2004) (U.S. EPA, 2009e)

Unlike ozone, PM causes damage to individuals in both short and long exposure periods. Many time series studies have linked daily concentrations of outdoor particles to daily variations in total and cause-specific mortality as well as emergency and unscheduled hospital admissions. However, two prominent public health researchers conclude that although studies have linked $PM_{2.5}$ concentrations and mortality, "on any given day, the number of people dying because of PM exposure in a population is small" (Pope & Dockery, 2006). A short-term increase of 50 $\mu g/m^3$ of $PM_{2.5}$ concentrations would result in about 1.2 deaths per day in a population of 1 million, compared with an expected death rate of 23.5 per day.

Short-term exposure contributes to morbidity and mortality, but long-term exposure to elevated $PM_{2.5}$ levels has a much more significant impact. Studies of the long-term effects of fine particle concentrations in the air "have suggested that even relatively low concentrations, when inhaled over a lifetime, can be associated with reduced survival" (Brunekreef, 1999). The Harvard Six Cities Study followed about 8,000 subjects in six eastern U.S. cities over 14 to 16 years. The study found that cities whose populations were consistently exposed to ambient air with higher concentrations of inhalable and fine particles had higher mortality rates correlated with the higher concentrations of PM. The study calculated rate ratios for incidence of mortality in cities with higher PM concentrations of 1.27 and 1.26. In other words, the number of deaths per person-years in cities with higher PM concentrations was 1.27 or 1.26 times the number of deaths per person-years in cities with lower concentrations. $PM_{2.5}$ varied between 35 and 20 $\mu g/m^3$ in high-PM cities and between 10 and 18 $\mu g/m^3$ in lower-concentration cities. The study found relationships between particulate air pollution and both deaths due to cardiopulmonary disease and incidence of lung cancer (Dockery et al. D. , 1993).

Another important longitudinal study through the American Cancer Society (ACS) followed 1.2 million adults starting in 1982. Researchers aimed to assess the relationship between long-term exposure to $PM_{2.5}$ and mortality from all causes, lung cancer, or cardiopulmonary causes. The study found that $PM_{2.5}$ pollution caused an increased risk of death in all three cases. A 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentrations was associated with a 4 percent increase in all-cause deaths, a 6 percent increase in cardiopulmonary-related deaths, and an 8 percent increase in deaths from lung cancer (Pope et al., 2002).

Particulate matter concentrations are associated with reported rates of chronic cough, bronchitis, and chest illness in children. In one study, “Children with a history of wheeze or asthma had a much higher prevalence of respiratory symptoms” (Dockery et al. D. , 1989). Studies also associate $PM_{2.5}$ concentrations with specific health effects in children, including decreased lung function and limited growth in lung function, in addition to increased respiratory illness and school absences. Evidence also links PM to post-neonatal respiratory mortality (Pope & Dockery, 2006).

Power Plant-Level Modeling

To estimate the health impacts of emissions from a particular power plant, developers must run two models; one to determine emissions trajectory and another to estimate health impacts to populations in the path of emissions. EPA maintains recommendations for its preferred air quality and health impact models and guidelines for acceptable and unacceptable models (U.S. EPA, 2005). States require air quality modeling from developers of stationary emission sources (e.g., power plants, industrial facilities) as part of the permitting process for constructing new facilities or making significant modifications to existing facilities. State agencies reference EPA’s guidelines regarding preferred models.

In 2005, EPA recommended American Meteorological Society/ Environmental Protection Agency Regulatory Model (AERMOD) as its preferred air dispersion model. Although other models could meet EPA’s guidelines, this paper will focus only on AERMOD because state agencies follow EPA’s recommendations for models in their air permitting processes. AERMOD was created by a joint committee of the American Meteorological Society and the EPA to bring the most advanced air quality modeling to the EPA. AERMOD “incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of both surface and elevated sources, and both simple and complex terrain” (U.S. EPA, 2010g). The model itself is composed of three programs; one provides information needed to characterize the terrain, one characterizes the surface, and the last is a dispersion model for the emissions plume.

To run the AERMOD model, a user needs precise data on the meteorological characteristics and climactic conditions of the source area from a source such as the National Weather Service, U.S. Geological Survey, an EPA-developed tool called AERSURFACE, or the National Climatic Data Center. The model includes optional controls for conditions such as urban settings and certain types of terrain. The AERMOD Implementation Guide outlines specific inputs to run the model and optional controls (AERMOD Implementation Workgroup, 2009). AERMOD’s output is the spatial and temporal dispersion of emissions from the point source.

EPA recommends two models to measure a population’s exposure to air pollutants; the Air Pollutant Exposure Model (APEX) and the Hazardous Air Pollutant Exposure Model (HAPEM). APEX estimates inhalation of ozone, PM, and air toxins at the local, urban, or metro area level and addresses only inhalation exposures. It “simulates the movement of individuals through time and space and their exposure to the given pollutant in various microenvironments.” The user is able to determine which microenvironments to include and the time period of the simulation. Inputs include air quality data from monitored data or a dispersion model like AERMOD, a Consolidated Human Activity Database that includes human activity models, and population and commuting pattern files from the U.S. Census Bureau. APEX provides hourly and summary exposure and/or dose estimates for each individual in the simulation and statistics for the entire population included in the model (U.S. EPA, 2009c). The long-term effects of short-term exposures may not be captured in this model.

HAPEM functions similarly to APEX but estimates exposures for subgroups within a population rather than for a population as a whole (U.S. EPA, 2007c). HAPEM uses activity pattern data, commuting spatial pattern and timing data, and demographic information as well as 14 indoor, in vehicle, and outdoor microenvironments to account for exposures in different settings. Ultimately, HAPEM provides the frequency and duration of exposure for specific demographic groups within various microenvironments. It then aggregates the exposures to provide a distribution of exposure concentrations for each demographic group in each census tract (ICF International, 2007).

Data from the models described above is used by states to determine whether the addition of a new source would meet "prevention of significant deterioration" of air quality; in other words, whether the addition of a new source would worsen air quality within an area such that it would not meet federal air quality standards. For this reason, analyses at the power plant level do not go a step beyond to quantify the health impacts of additional emissions. A developer or other interested party could take the exposure outputs from APEX or HAPEM and apply correlations from studies discussed above and EPA figures valuing a statistical life or cost of a hospital visit to create a rough estimate of health impacts. However, the additional emissions from a single gas-fired power plant are unlikely to contribute enough to increased ozone or PM concentrations to significantly impact public health; collectively, gas-fired power plants combined with coal-fired power and industrial facilities generate the impacts described earlier in this section.

Regional and National Modeling

Announcements about emissions regulation programs often include estimates of the savings in public health costs from avoided emissions (U.S. EPA, 2009f). EPA models the health impacts of regulatory scenarios and requires states to model their own policies to comply with state implementation plans (SIPs) used to carry out emissions reduction programs. These models predict the impact of a regulatory regime on a regional or statewide basis rather than at the plant level. For example, EPA estimates that reducing power plant emissions of SO_X and NO_X under its proposed Transport Rule would save between 14,000 and 16,000 lives and yield \$120 to \$290 billion in health and welfare benefits in 2014 (U.S. EPA, 2010h).

To provide an example, EPA modeled the effects, including environmental benefits, of a U.S. Senate proposal to alter existing cap and trade systems for power plant emissions. EPA used a simplified estimation method that applied a benefit-per-ton factor to tons of avoided emissions estimated through an air dispersion model. It used a factor derived from a peer-reviewed study updated with the standard

Value of a Statistical Life (VSL) from its Guidelines for Preparing Economic Analyses (U.S. EPA, 2000). In 2008 dollars, this value was $6.9 million[17] (Borenstein, 2008). To quantify the costs of avoided premature mortality due to reduced PM, EPA used factors derived from the Harvard Six Cities and American Cancer Society studies. To capture the benefits of ozone reductions, EPA used a factor from previous studies to estimate the benefit from all health endpoints rather than specific states or areas. In running several scenarios using a 3 percent discount rate, EPA found health benefits between $93 and $290 billion by 2025 (U.S. EPA, 2009d).

For a comprehensive analysis of health benefits of regulatory scenarios, EPA uses the Environmental Benefits and Mapping System (BenMAP). EPA used this model to quantify the benefits of its Clean Air Interstate Rule and related legislative proposals. BenMAP projects health impacts and associated economic benefits that occur when a population's air quality changes. It goes the step beyond health impact models to allow inputs for economic benefits associated with air quality improvements. To run a model estimating avoided premature deaths due to reduced $PM_{2.5}$ concentrations in an area, a user would input:

- The air pollution change as generated by an air dispersion model or a desired reduction;
- A mortality effect estimate, probably taken from epidemiological studies;
- The average mortality rate over a given period of time for the modeled population (available through World Health Organization data);
- The number of people impacted by the air pollution change; and
- The Value of a Statistical Life. (U.S. EPA, 2010e)

The case studies discussed later in this report will attempt to demonstrate how the structure of these models and their inputs can be useful in examining the health benefit of avoided emissions from a gas-fired power plant replaced by solar generation.

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[17] See Appendix F for an explanation and discussion of the Value of a Statistical Life

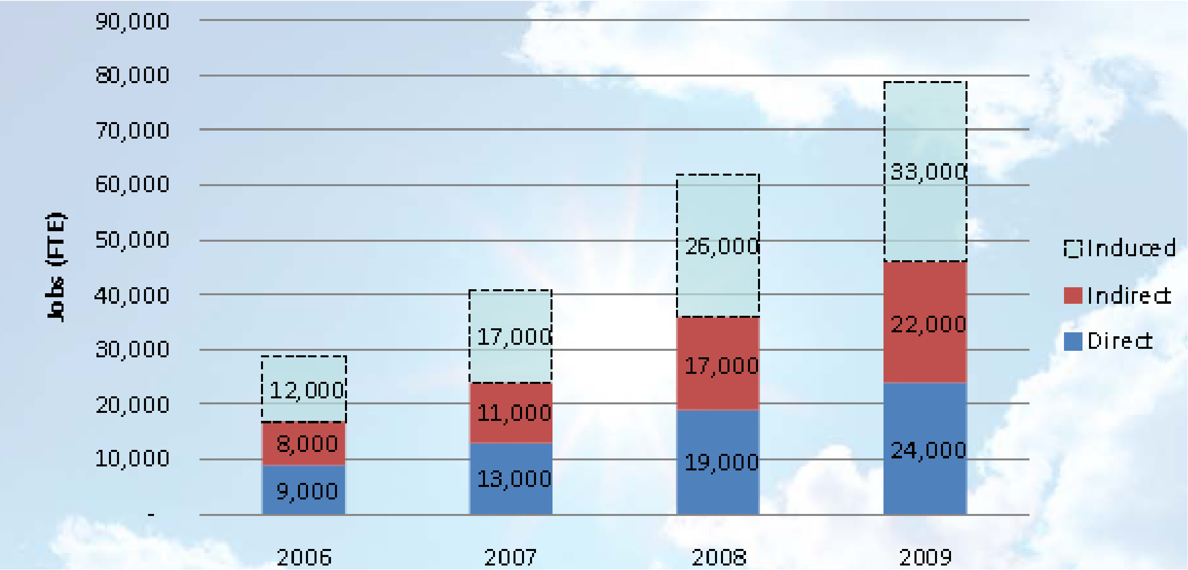
Chapter 5: Job Creation

Job creation is arguably the most publicized and debated among the ancillary impacts resulting from solar development. This section examines studies on the economy-wide job creation impacts of solar PV and other renewables compared to conventional generation, including the impacts of solar PV projects on the conventional generation industry and the implications of these impacts. It concludes with information about tools to model the job creation and economic impacts of solar energy projects.

Solar Energy Industry Employment

In 2008, 2.3 million people worldwide worked either directly in renewable energy industries or indirectly in supplier industries. The solar PV sector employs approximately 170,000 people, or 7 percent of this workforce (Renner, 2008). According to the Solar Energy Industry Association (SEIA), the U.S. solar industry supported 79,000 jobs in 2009, an increase of over 27 percent from 2008 (see Figure 48 below).

Figure 48. Estimated U.S. Solar Energy Employment



(SEIA, 2010)

As indicated in Figure 48, solar development creates three types of jobs: direct jobs, indirect jobs and induced jobs. Direct jobs refer to jobs created in the design, manufacture, delivery, and installation of solar modules and in the construction, project management, operations, and maintenance of solar power plants. Indirect jobs refer to the contributions of upstream and downstream suppliers to the PV industry. A steel manufacturer that builds frames for solar modules is an example of an indirect job. Induced jobs account for expenditure-induced effects in the general economy due to economic activity and spending of direct and indirect employees. Essentially an induced job is created through the spent earnings of the direct workers. Examples include grocery store clerks, and postal workers in areas where direct and indirect employees live and spend money (Wei, Patadia, & Kammen, 2009).

Of the 79,000 individuals employed in the solar industry in 2009: 24,000 were directly employed in the solar industry, 22,000 worked for companies that supply services and materials to the solar industry, and 33,000 were induced jobs supported by the solar industry (SEIA, 2010).

Solar Jobs vs. Traditional Energy Generation Jobs

Solar PV tends to be more labor intensive than traditional fossil fuel generation. However established technologies such as coal or natural gas strive for efficiency gains in terms of jobs per unit of output. Thus, it is important to acknowledge that some will argue that the development of solar resources is in essence the promotion of a labor intensive technology over more efficient ones.

The number of jobs in the fossil fuel industry decreased in the last decade. This is largely due to automation and industry consolidation, factors that are independent of renewable energy development. Coal energy production in the U.S. increased by almost one third over the past 20 years, yet employment in this sector was cut in half (Renner, 2008). The U.S. Bureau of Labor Statistics (BLS) includes “support activities for mining” among the ten industries it expects to experience the largest decline in employment over the next 10 years. BLS projects that employment in this sector will decline from 330,000 to 250,000 jobs by 2018 (about a 25 percent decrease) due to continued mechanization, consolidation, and the transition to a clean energy economy (U.S. BLS, 2009).

The shift from fossil fuel resources to renewable energy sources will also affect employment in the fossil fuel sector. Renewable energy industries rely more heavily on manufacturing than fossil fuel industries. If the U.S. continues to transition into a clean energy economy, jobs in the energy sector are likely to shift from mining and related services to manufacturing and construction. As discussed in the next section, the solar energy industry generates more jobs per average MW of production and per dollar invested than fossil fuel-based industries (Wei, Patadia, & Kammen, 2009).

Factors outside the Scope of this Analysis

The recent global financial crisis, the development of other “green” sectors such as energy efficiency and sustainable transportation, and the increased usage of electric vehicles, among others could affect the demand for solar energy in the U.S. While this study recognizes that such macroeconomic factors could affect employment in the solar energy industry, it does not attempt to predict the effects of such factors.

Review of Existing Estimates of Jobs Created due to Solar PV Development

This study did not find any credible reports concluding that developing solar energy resources will create a net decrease in jobs. Conversely, within the past decade numerous published studies have supported the view that developing solar energy does indeed lead to a net increase in jobs.

The University of California Berkeley, the California Public Interest Research Group (CALPIRG) and BBC Research and Consulting each published reports examining job creation as a result of PV deployment in the U.S. These reports analyzed the number and type of jobs created from various technologies and applications including residential and commercial roof-tops, concentrated solar power, and solar-thermal, but the specific focus of this report is on PV utility-scale ground mounted solar development. The results of these studies are summarized in the sections below.

When interpreting the results of these analyses it is important to distinguish between person-years per MW and jobs per MW. A person-year per MW refers to the amount of labor required to manufacture equipment or to build a power plant for every MW of power. Manufacturing and construction jobs are typically reported in this unit. O&M and fuel processing jobs, however, are reported in jobs per MW. The unit "job per MW" refers to the number of people needed to provide the ongoing operation of a plant for every MW of power that the plant provides.

University of California Berkeley

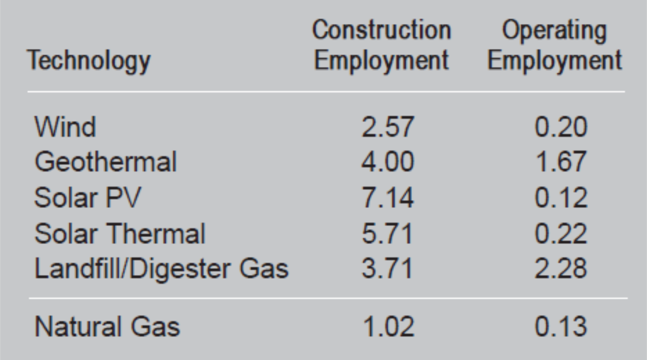
The University of California Berkeley reviewed 15 recent studies on the job creation potential of renewable energy, energy efficiency, and low carbon sources such as carbon capture and sequestration, and nuclear power. Berkeley concluded that renewable energy creates more jobs per unit of energy than coal, natural gas, and common renewable energy technologies (Wei, Patadia, & Kammen, 2009).

California Public Interest Research Group

CALPIRG also examined the impacts of renewable energy development on job creation in California. Like the Berkeley study, CALPIRG also found that generating electricity from renewable energy sources such as solar provides more jobs than traditional energy sources (CALPIRG, 2002). In its study, CALPIRG finds that building 5,900 MW of capacity from renewable resources would create 120,766 jobs, while natural gas development of the same capacity would only create 29,028 jobs.

CALPIRG cited EPRI data that showed that solar PV created 7.41 construction jobs per MW, the greatest number of construction jobs when compared to natural gas and to other renewable energy technologies (see Figure 49). These figures include direct (at generating facility) and indirect (component manufacturing) jobs. EPRI's results also show that solar PV creates the least number of O&M jobs per MW, however.

Figure 49. Employment Rates by Energy Technology (Jobs/MW)

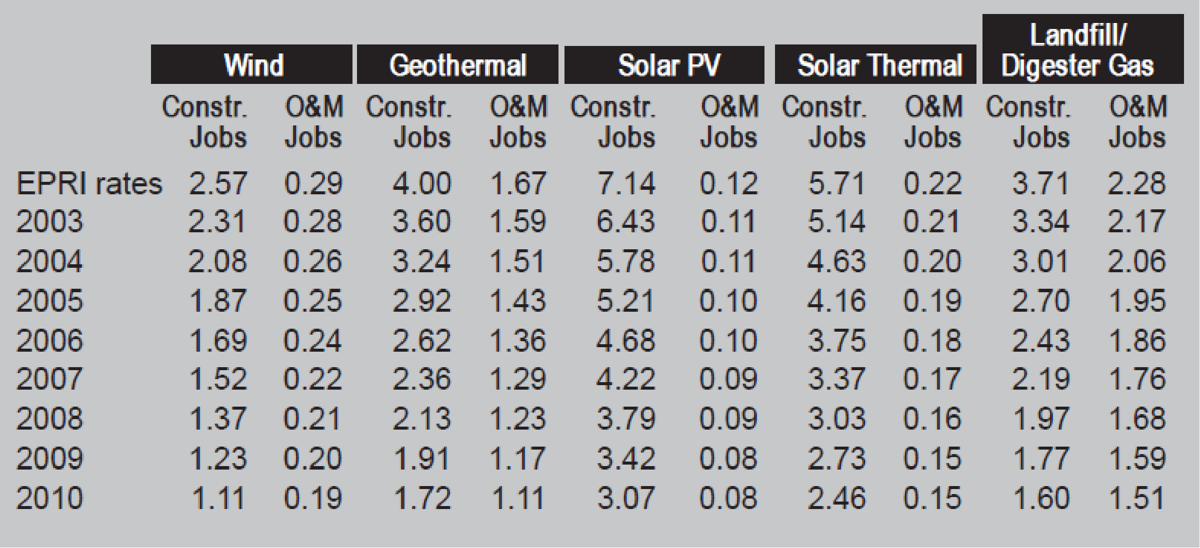


Technology	Construction Employment	Operating Employment
Wind	2.57	0.20
Geothermal	4.00	1.67
Solar PV	7.14	0.12
Solar Thermal	5.71	0.22
Landfill/Digester Gas	3.71	2.28
Natural Gas	1.02	0.13

(CALPIRG, 2002)

CALPIRG used the EPRI data to forecast employment rates from 2003 to 2010. CALPIRG assumed a decrease of 10 percent per year in the construction employment rate and 5 percent per year in the operation and maintenance employment rate over the next decade due to economies of scale and increased experience of renewable energy companies (see Figure 50). (These calculations were solely for the state of California and are not reflective of other states and regions.)

Figure 50. EPRI Employment Rates with Annual Reduction (Jobs/MW)



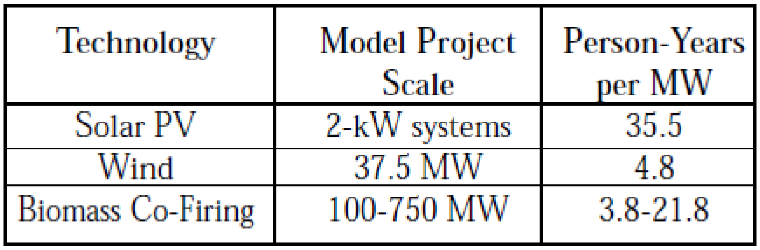
	Wind		Geothermal		Solar PV		Solar Thermal		Landfill/ Digester Gas	
	Constr. Jobs	O&M Jobs	Constr. Jobs	O&M Jobs	Constr. Jobs	O&M Jobs	Constr. Jobs	O&M Jobs	Constr. Jobs	O&M Jobs
EPRI rates	2.57	0.29	4.00	1.67	7.14	0.12	5.71	0.22	3.71	2.28
2003	2.31	0.28	3.60	1.59	6.43	0.11	5.14	0.21	3.34	2.17
2004	2.08	0.26	3.24	1.51	5.78	0.11	4.63	0.20	3.01	2.06
2005	1.87	0.25	2.92	1.43	5.21	0.10	4.16	0.19	2.70	1.95
2006	1.69	0.24	2.62	1.36	4.68	0.10	3.75	0.18	2.43	1.86
2007	1.52	0.22	2.36	1.29	4.22	0.09	3.37	0.17	2.19	1.76
2008	1.37	0.21	2.13	1.23	3.79	0.09	3.03	0.16	1.97	1.68
2009	1.23	0.20	1.91	1.17	3.42	0.08	2.73	0.15	1.77	1.59
2010	1.11	0.19	1.72	1.11	3.07	0.08	2.46	0.15	1.60	1.51

(CALPIRG, 2002)

BBC Research and Consulting

In 2001, Virinder Singh with BBC Research and Consulting and Jeffrey Fehrs published a report examining the jobs involved in all stages of renewable energy projects (Singh & Fehrs, 2001). Singh and Fehrs surveyed firms in the PV and wind industries that have operations in the U.S. They used the survey data to estimate the total hours required to manufacture, install and service wind power and solar PV. Singh and Fehrs founds that PV creates more jobs on an energy capacity basis than both wind and biomass co-firing plants (see Figure 51).

Figure 51. Labor Requirements for Renewable Energy Technologies

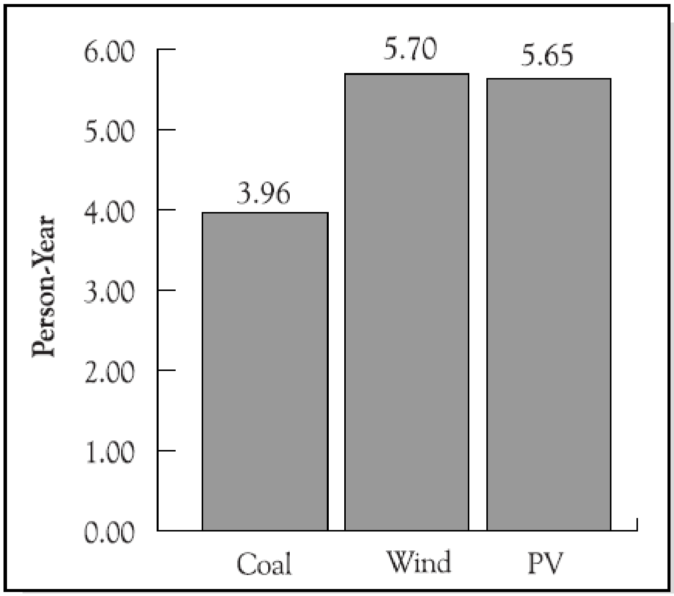


Technology	Model Project Scale	Person-Years per MW
Solar PV	2-kW systems	35.5
Wind	37.5 MW	4.8
Biomass Co-Firing	100-750 MW	3.8-21.8

(Singh & Fehrs, 2001)

Singh and Fehrs also found that solar PV creates 40 percent more jobs per dollar invested than coal (see Figure 52 below).

Figure 52. Person-Years per $1 Million in Cost over 10 Years (Including Capital and Construction)



(Singh & Fehrs, 2001)

The results of the Berkeley, CALPIRG, and other studies show that modeling the economic impacts of solar and other renewable energy projects without considering jobs creation and other ancillary benefits does not accurately reflect the true economic impact. Furthermore, the results of the studies show that solar produces more jobs per MW of installed capacity than any other source of energy.

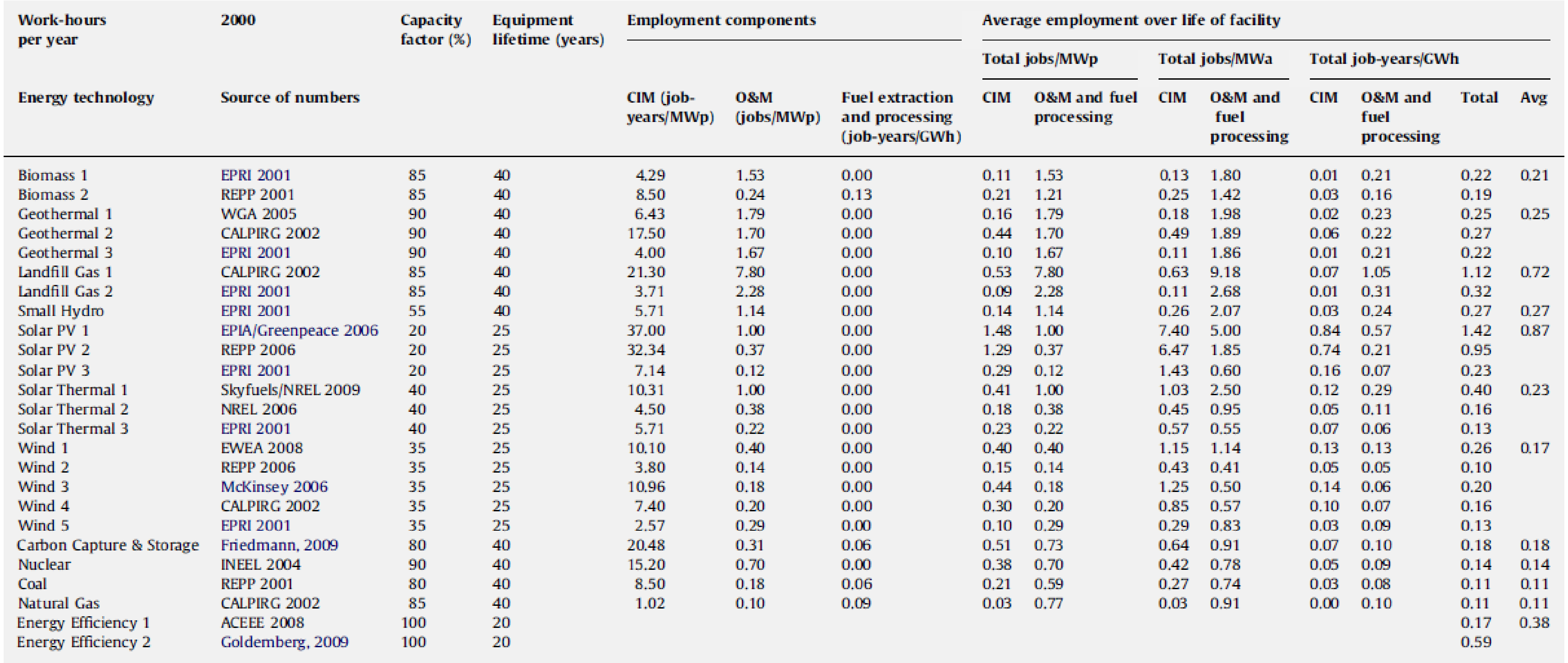
Factors to Consider when Interpreting Results

When interpreting job creation estimates it is important to determine the specific jobs created or lost within the energy industry. Jobs in the energy industry can typically be divided into the following categories: manufacturing, construction, installation, O&M, fuel production, extraction, and processing. For a particular state or region, even if the net number of jobs lost or gained from the transition from traditional to renewable energy resources is zero, there may be a shift in the type of jobs available. Thus, it is important to know what types of jobs are being lost, and what types are created in order to determine the sorts of retraining and retooling needed (Wei, Patadia, & Kammen, 2009).

Distinguishing between different types of jobs is also important because job types will grow at different rates as the solar energy industry grows. For example, growth in the solar industry could lead to increased manufacturing jobs to meet export demands, without a corresponding increase in O&M jobs.

Figure 53 below compares the jobs created per unit of power delivered from different renewable energy technologies. This figure is included to illustrate two points. First, the studies referenced in this table reached different conclusions regarding number and type of jobs, even within the same technology. Second, not all renewable energy technologies produce the same type and number of jobs, which is important to keep in mind if a potential site has different technology options for development.

Figure 53. Comparison of Jobs/MWp and Job-years/GWh Across Technologies



Work-hours per year	2000	Capacity factor (%)	Equipment lifetime (years)	Employment components			Average employment over life of facility							
							Total jobs/MWp		Total jobs/MWa		Total job-years/GWh			
Energy technology	Source of numbers			CIM (job-years/MWp)	O&M (jobs/MWp)	Fuel extraction and processing (job-years/GWh)	CIM	O&M and fuel processing	CIM	O&M and fuel processing	CIM	O&M and fuel processing	Total	Avg
Biomass 1	EPRI 2001	85	40	4.29	1.53	0.00	0.11	1.53	0.13	1.80	0.01	0.21	0.22	0.21
Biomass 2	REPP 2001	85	40	8.50	0.24	0.13	0.21	1.21	0.25	1.42	0.03	0.16	0.19	
Geothermal 1	WGA 2005	90	40	6.43	1.79	0.00	0.16	1.79	0.18	1.98	0.02	0.23	0.25	0.25
Geothermal 2	CALPIRG 2002	90	40	17.50	1.70	0.00	0.44	1.70	0.49	1.89	0.06	0.22	0.27	
Geothermal 3	EPRI 2001	90	40	4.00	1.67	0.00	0.10	1.67	0.11	1.86	0.01	0.21	0.22	
Landfill Gas 1	CALPIRG 2002	85	40	21.30	7.80	0.00	0.53	7.80	0.63	9.18	0.07	1.05	1.12	0.72
Landfill Gas 2	EPRI 2001	85	40	3.71	2.28	0.00	0.09	2.28	0.11	2.68	0.01	0.31	0.32	
Small Hydro	EPRI 2001	55	40	5.71	1.14	0.00	0.14	1.14	0.26	2.07	0.03	0.24	0.27	0.27
Solar PV 1	EPIA/Greenpeace 2006	20	25	37.00	1.00	0.00	1.48	1.00	7.40	5.00	0.84	0.57	1.42	0.87
Solar PV 2	REPP 2006	20	25	32.34	0.37	0.00	1.29	0.37	6.47	1.85	0.74	0.21	0.95	
Solar PV 3	EPRI 2001	20	25	7.14	0.12	0.00	0.29	0.12	1.43	0.60	0.16	0.07	0.23	
Solar Thermal 1	Skyfuels/NREL 2009	40	25	10.31	1.00	0.00	0.41	1.00	1.03	2.50	0.12	0.29	0.40	0.23
Solar Thermal 2	NREL 2006	40	25	4.50	0.38	0.00	0.18	0.38	0.45	0.95	0.05	0.11	0.16	
Solar Thermal 3	EPRI 2001	40	25	5.71	0.22	0.00	0.23	0.22	0.57	0.55	0.07	0.06	0.13	
Wind 1	EWEA 2008	35	25	10.10	0.40	0.00	0.40	0.40	1.15	1.14	0.13	0.13	0.26	0.17
Wind 2	REPP 2006	35	25	3.80	0.14	0.00	0.15	0.14	0.43	0.41	0.05	0.05	0.10	
Wind 3	McKinsey 2006	35	25	10.96	0.18	0.00	0.44	0.18	1.25	0.50	0.14	0.06	0.20	
Wind 4	CALPIRG 2002	35	25	7.40	0.20	0.00	0.30	0.20	0.85	0.57	0.10	0.07	0.16	
Wind 5	EPRI 2001	35	25	2.57	0.29	0.00	0.10	0.29	0.29	0.83	0.03	0.09	0.13	
Carbon Capture & Storage	Friedmann, 2009	80	40	20.48	0.31	0.06	0.51	0.73	0.64	0.91	0.07	0.10	0.18	0.18
Nuclear	INEEL 2004	90	40	15.20	0.70	0.00	0.38	0.70	0.42	0.78	0.05	0.09	0.14	0.14
Coal	REPP 2001	80	40	8.50	0.18	0.06	0.21	0.59	0.27	0.74	0.03	0.08	0.11	0.11
Natural Gas	CALPIRG 2002	85	40	1.02	0.10	0.09	0.03	0.77	0.03	0.91	0.00	0.10	0.11	0.11
Energy Efficiency 1	ACEEE 2008	100	20										0.17	0.38
Energy Efficiency 2	Goldemberg, 2009	100	20										0.59	

(Wei, Patadia, & Kammen, 2009)

JEDI Model

Few models developed to analyze the economic impact of renewable energy technologies are available to the public. The Job and Economic Development Impact (JEDI) Model developed by NREL is publicly available and provides a strong basis for understanding and evaluating job creation from a particular project. The JEDI model provides an estimate of the total direct, indirect, and induced jobs created from a particular project, and an estimate of the earnings and total economic output from these jobs and of the tax revenue generated as a result of the project.

NREL currently publishes 7 JEDI models: wind, cellulosic biofuels, corn ethanol biofuels, CSP trough, solar PV, natural gas, and coal. Each model leverages the same basic methodology and uses dollars spent on power generation in a state, county or region to determine the employment and economic impact within the local area. The variety of models published by the NREL allows users to compare job creation among different types of renewable energy technologies as well as traditional fossil fuel resources.

Types of Employment Models

Models developed to calculate the employment impacts of the renewable energy industry can be divided into two main categories: (1) input-output (I-O) economic models, and (2) simpler, largely spreadsheet-based analytical models. Analytical models generally calculate only the direct employment impacts. I-O models capture the direct jobs calculated by analytical models and also account for indirect jobs (Wei, Patadia, & Kammen, 2009).

I-O models generally provide the most comprehensive picture of the impact of a particular solar project on the economy as a whole. Most I-O models also include shifts between sectors and thus account for the losses in one sector (e.g. natural gas) spurred by the growth of another sector (e.g. solar). Analytical models usually ignore these counter effects and thus may not be as accurate in calculating the holistic economic impact (Wei, Patadia, & Kammen, 2009).

But, I-O models are generally designed to model only one scenario; changing the model to incorporate new data or different scenarios is extremely difficult. Given the model's inflexibility, the results generated by I-O models must be considered carefully under differing local, state, or regional policies and regulations. Analytical models, however, are much clearer in their assumptions and more suited to conducting sensitivity analyses of different regulatory scenarios (Wei, Patadia, & Kammen, 2009).

Although the JEDI model is an I-O model, it allows the user to adjust assumptions easily and is more flexible than a typical I-O model. The JEDI model is not intended to provide a precise forecast, but rather an estimate of overall economic impacts for specific projects.

Data Used

JEDI models utilize economic data (multipliers and consumption patterns) from the Minnesota IMPLAN Group (MIG) and these factors can be accessed and adjusted. The MIG compiles and aggregates national and regional economic and demographic data to calculate inter-industry linkages and the relationships between changes in demand for goods and services, and the associated economic activity at the local, state and regional levels. The JEDI model also incorporates a variety of tax factors that enable it to provide the tax impact on both a local and state level.

Prevailing Wage Assumptions

The assumption for prevailing wages is an important factor that impacts the results of the JEDI model. For the purposes of validating the model, this study compared the prevailing wage for Massachusetts of $27.49 to the annual salary of an electrician from the Commonwealth of Massachusetts and found that they are approximately equal.

JEDI Model Results

The output of the JEDI model includes number of jobs created, earnings (wages and salaries), and output (all economic activity related to the project) for direct, indirect, and induced jobs for both the construction and operating period of the renewable energy project. (See Appendix G for screen shots of the input and results pages of the JEDI model.)

The community impact of developing a solar project is very region- and project-specific and comes from two main sources: induced jobs and increased local and state tax revenues generated by a project. The JEDI model attempts to capture the impact of solar development through the creation of induced jobs and tax impact based on where the project will be located. How these incremental tax dollars will eventually benefit the local communities is dependent on factors specific to the area or region.

The JEDI model is the best, most objective option available among the models examined because it is easy to understand and use, widely used among a variety of stakeholders, and produced by a government agency. It has been used by a variety of stakeholders related to both the wind and solar industries including county and state decision-makers, public utility commissions and potential project owners. Solar industry advocacy group Vote Solar has used the JEDI model for numerous reports that analyze the economic impact of solar development in various states.

It is also important to acknowledge that a higher number of jobs created in and of itself is not justification that one technology should be pursued versus another. Other factors beyond the scope of this paper, such as where panels are sourced (U.S. versus international) should be considered if one is to understand the full economic impact of solar development for a particular region, state, or nation. In addition, wind and PV are less developed technologies than conventional power plants, and a higher number of jobs created may be an indication of inefficiency as compared to more developed energy resources such as coal or natural gas.

Case Studies

As discussed in the preceding sections, the ancillary impacts associated with solar PV are largely affected by the local environment and the generation mix of the grid. In this section, the study attempts to apply the five ancillary solar impacts outlined in the previous chapters for actual solar projects currently under development by Axio Power: Greenfield (Massachusetts), IC Sunshine (Hawaii) and Hi Desert (California). These three projects will operate in different electrical markets. California is largely a natural gas and hydro-powered state, Hawaii depends almost exclusively on petroleum for electricity, while Massachusetts most closely mirrors national generation mix averages.

Greenfield Solar Project

The Greenfield Solar project is a 2 MW solar PV project located on a 22.5 acre closed landfill in the town of Greenfield, Massachusetts under development by Axio Power. Construction is scheduled to be completed by the end of the second quarter of 2011. Using 16,528 Sharp thin film PV panels, the project will generate 2,996 MWh of electricity per year without drawing significant amounts of water from the water table and generate tax revenue from previously unusable land. It will also avoid NO_X and CO_2 emissions, prevent health problems related to NO_X emissions in the local community, and bring new jobs to the area.

Each particular region of the United States is characterized by a unique fuel mix and required pollution controls for the electricity grid, resulting in different emissions factors for different regions of the grid. The Greenfield project is located in the NEWE sub-region as defined by the EPA. The NEWE sub-region electricity generation mix is comprised of: 15.2 percent coal, 9.8 percent oil, 36.6 percent (natural) gas, 5.3 percent biomass, 6 percent hydro, 25.6 percent nuclear with the remaining generation coming from other fossil fuels and wind.

Water Use

Water resources play an important role in the operation of a thermoelectric power plant (i.e., a power plant that uses coal, natural gas, oil, or nuclear fuel source). Approximately 99 percent of thermoelectric power plants in the U.S. rely on local saline or freshwater sources to provide cooling water used to condense the exhaust steam from the turbine-generator (NETL, 2009). Although power plants do not consume all of the water withdrawn from the water source, their operation depends on reliable access to a local water supply.

The amount of local water needed to generate electricity using the Greenfield project is significantly smaller than the amount of local water needed to generate electricity from the U.S. grid or from a NGCC plant of an equivalent size.

Local Water	From the U.S. Grid[18]		From a NGCC plant	
Savings	Annually	Lifetime[19]	Annually	Lifetime[20]
Withdrawals (gallons)	56.67 million	1.06 billion	838,560	15.67 million
Consumption (gallons)	2.03 million	37.95 million	783,110	14.63 million

Source: Appendix H

In order to generate electricity, the U.S. grid withdraws approximately 18,924 gallons per MWh of production and consumes approximately 686 gallons per MWh. A NGCC plant[21] withdraws approximately 289 gallons per MWh and consumes 270 gallons per MWh. The Greenfield project is estimated to produce 2,996 MWh of electricity in the first year of production. If this electricity were generated by the U.S. grid, it would withdraw 56.69 million gallons and consume 2.06 million gallons of water. If this electricity were generated at a NGCC plant, it would withdraw 864,365 gallons and consume 808,920 gallons.

The operation of PV technologies requires water, which is used to clean and cool the wafers, cells, and modules. Each module of a solar PV plants withdraws and consumes approximately 1.1 gallons of water per m^2 of module area per year. The Greenfield project will include 23,498 m^2 of module area and will withdraw and consume approximately 25,806 gallons per year.

In the first year of production, the Greenfield project will therefore **save 1.06 billion gallons** in water withdrawals and **37.95 million gallons** in water consumption when compared to the U.S. grid over the 20 year lifetime of the PV plant; and will **save 15.67 million gallons** in water withdrawals and **save 14.63 million gallons** in water consumption when compared to a NGCC plant over the 20 year lifetime of the PV plant.

Looking at the entire life cycle of a PV panel, the production and processing of raw materials (upstream processes) and the manufacturing process used to make the panel consume significant amounts of electricity. The electricity used to produce silicon and to grown single crystals is generated primarily from thermoelectric power plants, which are water intensive (see Appendix B) (Kim, 2010). PV modules are not manufactured near Greenfield, MA; PV panel production, therefore, does not affect the local water supply for this project. But this water use will affect the global water supply.

The Greenfield project will include 16,528 silicon thin film modules. The electricity used in production and processing of silicon and the manufacturing process for these modules requires withdrawals of approximately **1.7 million gallons** of water. (Water consumption data for PV module manufacturing is

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[18] See Appendix H for assumptions regarding the breakdown of U.S. net generation by fuel type and by cooling system type.

[19] Assuming a 0.7% annual degradation factor

[20] Assuming a 0.7% annual degradation factor

[21] This analysis assumes that most NGCC plants built after 2010 will use a wet recirculating cooling system. The use of closed-loop systems is likely to be more common in the future due to Clean Water Act provisions and public pressures. It is most likely that dry cooling will represent a small percentage of total combined cycle cooling (NETL 2009). The calculations included in this case studies uses withdrawal and consumption factors for a NGCC plant that uses a wet recirculating system.

not available.) Looking at the global water supply, therefore, the water savings associated with the Greenfield project would be reduced to **1.059 billion gallons** of water when compared to the U.S. grid and to **13.95 million gallons** when compared to a NGCC.

Avoided CO_2 Emissions

The Greenfield project will produce electricity without generating CO_2 emissions. In order to understand exactly how significant this is, the study compares these savings to what would have been generated by the local electricity grid and also by an equivalent size natural gas power plant.

CO_2	**From the Grid**		**From a Natural Gas Facility**	
Savings	**Annually**	**Lifetime[22]**	**Annually**	**Lifetime[23]**
Emissions (lbs)	2,779,329	52,040,814	3,400,460	63,671,011
Equiv. cars[24]	243	4,545	296	5,560
Costs ($)	$27,793	$520,408	$34,005	$636,710

From the Grid

Given the specific generation mix of fuel for the NEWE sub-region and required pollution controls, CO_2 emissions from the grid in NEWE occur at the rate of 927.68 lb/MWh[25] of generated electricity (U.S. EPA, 2008b). This rate is lower than the national average largely due to the state's reliance on nuclear power and natural gas for more than 60 percent of its electricity generation. The Greenfield project is estimated to produce 2,996 MWh of electricity in the first year of production, thus **avoiding 2,779,329 lbs** of CO_2 emissions in the first year of production, which is equivalent to taking 243 cars off the road for one year. Recent estimates for short term and long term carbon prices have ranged from $10-$47 per ton of CO_2e (Capoor & Ambrosi, 2009). Assuming a price of $20 per ton of CO_2, the Greenfield project will save **$27,793** in CO_2 allowances that would have otherwise been purchased in the first year. Over a 20-year period (the life of the plant – assuming a 0.7 percent annual production degradation), this will prevent 52,040,814 lbs of CO_2 from being emitted and $520,408 in avoided emissions permitting or reduction cost.[26] If the U.S. adopts legislation to place a price on carbon, the avoided CO_2 from solar electricity generation will become more valuable assuming the price of carbon is likely rise over time.

From a Natural Gas Facility

According to the EPA, a natural gas generation facility will emit 1135 lbs of CO_2 per MWh of electricity generated (U.S. EPA, 2007a). On average, a PV facility the size of Greenfield would **avoid 3,400,460 lbs of CO_2** in its first year of operation from being emitted into the atmosphere. At an average cost of $20/ton $CO_{2,}$ this would save **$34,005** in avoided CO_2 permits in the first year of production. Over the 20-year life of the PV plant (assuming a 0.7 percent annual degradation factor), the solar facility could be

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[22] Assuming a 0.7% annual degradation factor

[23] Assuming a 0.7% annual degradation factor

[24] Equivalent cars refers to the equivalent number of cars removed from the road based on EPA reported U.S. transportation averages.

[25] The emissions factor of 927.68 lbs CO_2 per MWh is an average for natural gas plants in the NEWE sub-region. This factor is not specific to a NGCC plant because reliable averages for NGCC are not currently available.

[26] Assuming a constant $20/lb CO_2 with no discounting

expected to avoid **63,671,011 lbs of CO_2** emissions. At an average cost of \$20/ton CO_2, Greenfield could be expected to save **\$636,710** in avoided allowance costs over the 20-year life of the PV facility.[27]

Avoided NO_X Emissions

The Greenfield Project will produce electricity without generating NO_X emissions. In order to understand exactly how significant this is, the study compares these savings to what would have been generated by the local electricity grid and also by an equivalent size natural gas power plant.

NO_X	**From the Grid**		**From a Natural Gas Facility**	
Savings	**Annually**	**Lifetime[28]**	**Annually**	**Lifetime[29]**
Emissions (lbs)	2,586	48,412	5,093	95,366
Equiv. cars[30]	68	1,267	133	2,496
Costs (\$)	\$1,422	\$26,627	\$2,801	\$52,451

From the Grid

Given the specific generation mix of fuel for the NEWE sub-region and required pollution controls, NO_X emissions from the grid in NEWE occur at the rate of 0.863 lb/MWh[31] of generated electricity (U.S. EPA, 2008b). The Greenfield project is estimated to produce 2,996 MWh of electricity in the first year of production. Thus, the Greenfield Project will **avoid 2,586 lbs** of NO_X emissions in the first year of production. At a price of \$1,100/ton[32] of NO_X, this will **save \$1,422** in NO_X allowances that would have otherwise been purchased. Over a 20-year time period (the life of the plant – assuming 0.7 percent annual production degradation), this will **prevent 48,412 lbs** of NO_X emissions and **\$26,627**[33] in avoided emissions permitting costs.

From a Natural Gas Facility

According to the EPA, a natural gas generation facility will emit 1.7 lbs of NO_X per MWh of electricity generated (U.S. EPA, 2007a), although this number varies across the country depending on various required NO_X emissions controls. On average, a PV facility the size of Greenfield would **avoid 5,093 lbs of NO_X** emissions in its first year of operation**;** at an average cost of \$1,100/ton of NO_X emitted, this would save **\$2,801** in avoided NO_X permits in the first year of production. Over the 20-year life of the PV plant (assuming a 0.7 percent annual degradation factor), the solar facility could be expected to offset **95,366 lbs** of NO_X emissions. At an average cost of \$1,100/ton NO_X, Greenfield could be expected to save **\$52,451** in avoided permit costs over the 20-year life of the PV facility.

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[27] Assuming a constant \$20/lb CO_2 with no discounting

[28] Assuming a 0.7% annual degradation factor

[29] Assuming a 0.7% annual degradation factor

[30] Equivalent cars refers to the equivalent number of cars removed from the road based on EPA reported U.S. transportation averages.

[31] The emissions factor of 0.863 lbs NO_X per MWh is an average for natural gas plants in the NEWE sub-region. This factor is not specific to a NGCC plant because reliable averages for NGCC are not currently available.

[32] This is the EPA's projected price of NO_X allowances for 2010. Source: Beth Murray – Clean Air Markets Division – May 2009.

[33] Assuming a constant \$600/lb NO_X with no discounting

Health Impacts to the Community

NO_X emissions from a natural gas-fired power plant at the Greenfield site could be expected to impact the health of local populations, particularly in the summer. Related to NO_X emissions, high atmospheric concentrations of ozone levels are a problem in Massachusetts, particularly in western Massachusetts, where Greenfield is located. The state of Massachusetts is in nonattainment for national eight-hour average ozone standard, and one of the air monitors that consistently shows standard violations, Chicopee, is located south and upwind of Greenfield. The high concentration of ozone in this area can be mainly attributed to upwind sources in other states, especially during days of high electricity demand. These days generally occur in the summer, when the meteorological conditions are ripe for ozone formation (MA DEP, 2008).

High concentrations of ozone aggravate respiratory conditions including asthma, and Massachusetts has one of the highest rates of asthma in the country. Nationally, an estimated 9.3 percent of children and 7.3 percent of adults have asthma; in Massachusetts, these estimates are 10.3 percent and 9.9 percent respectively. Asthma is also an increasingly expensive public health problem. Between 2000 and 2006, the total amount charged to patients hospitalized for asthma increased from \$50 million to \$89 million, a rise of 77.7 percent (MA DPH, 2009). Although NO_X -related pollutants such as ozone and particulate matter from a single NGCC plant with modern technology have little impact on public health, the cumulative impact of individual decisions to allow polluting facilities has led to high ozone concentrations. As discussed earlier, days of peak power demand lead to higher emissions levels of ozone precursors like NO_X from power production, which then react to form ozone. Solar PV is producing at its peak during this time and competing directly with the peaking plants producing NO_X pollution. Replacing peaking natural gas facilities with solar PV on a broad scale should reduce ozone concentrations—and public health concerns related to ozone such as asthma—when they are currently highest, during peak power production.

Job Creation

NREL’s JEDI model forecasts that the Greenfield project will generate **55 jobs during its construction and installation phase**. This includes **13 direct construction and installation** jobs and **5 direct engineering, design and other professional service jobs** associated with project development. **24 indirect jobs** will be created from inter-industry purchases resulting from direct final demand (i.e. spending on materials and PV equipment and other purchases of goods and offsite services). Lastly the JEDI model forecasts that **12 induced jobs** will come about because of this project. Producing the same electricity from a natural gas plant would create 2 construction and installation jobs and no new operations and maintenance jobs.

In total, these jobs will generate approximately \$3.9 million in pre-tax earnings and total economic output of \$8.4 million. No new jobs are created for ongoing maintenance and operations. However, the project yields a positive impact through estimated annual earnings of \$12,900 and economic output of \$17,500.

Local Economic Impacts - Summary Results			
	Jobs	**Earnings**	**Output**
During construction and installation period		**$000 (2010)**	**$000 (2010)**
Project Development and Onsite Labor Impacts	18	$1,385.6	$1,760.3
Construction and Installation Labor	13	$1,020.4	
Construction and Installation Related Services	5	$365.2	
Module and Supply Chain Impacts	24	$1,856.2	$4,704.0
Induced Impacts	12	$724.4	$1,966.9
Total Impacts	**55**	**$3,966.2**	**$8,431.2**
		Annual	**Annual**
	Annual	**Earnings**	**Output**
During operating years	**Jobs**	**$000 (2010)**	**$000 (2010)**
Onsite Labor Impacts			
PV Project Labor Only	0	$10.2	$10.2
Local Revenue and Supply Chain Impacts	0	$1.5	$4.1
Induced Impacts	0	$1.2	$3.2
Total Impacts	**0**	**$12.9**	**$17.5**

Notes: Earnings and Output values are thousands of dollars in year 2010 dollars. Construction and operating period jobs are full-time equivalent for one year (1 FTE = 2,080 hours). Economic impacts "During operating years" represent impacts that occur from system/plant operations/expenditures. Totals may not add up due to independent rounding.

Incentives that allow solar developers to waive many taxes make Massachusetts a unique state in which to measure ancillary economic impacts of a solar project. Massachusetts waives taxes that would otherwise create revenue in order to attract solar development. Thus, the bulk of the economic impact to the community comes from a deep queue of projects and continual creation of construction and installation jobs.

IC Sunshine Solar Project

The IC Sunshine Solar Project under development by Axio Power is a 5 MW solar PV project located on 20 acres of land that was previously contaminated from an oil refinery in the town of Kapolei, Hawaii. Construction is scheduled to be completed in the fourth quarter of 2011. Using 28,533 Canadian Solar poly-crystalline PV panels, the project will generate 9,276 MWh of electricity per year without using significant amounts of water and will generate tax revenue from previously unusable land. It will also avoid NO_X and CO_2 emissions and bring new jobs to the area.

Each particular region of the United States is characterized by a unique fuel mix and required pollution controls, resulting in different emissions factors for different regions of the grid. The IC Sunshine project is located in the HIOA sub-region as defined by the EPA. The HIOA sub-region generation mix is comprised of: 18.9 percent coal, 77 percent oil, and 2.3 percent other fossil fuels, and 1.8 percent biomass.

Water Use

A discussion of freshwater use is not relevant to the IC Sunshine project. The Hawaiian Electric Company (HECO) generates over 95 percent of the electricity used on the island of Oahu (HECO). In order to generate this electricity, HECO's power plants use once-through cooling systems that withdraw water from the Pacific Ocean (U.S. EIA, 2005). The IC Sunshine project, therefore, will not displace freshwater withdrawals or consumption.

The operation of PV technologies requires water, which is used to clean and cool the wafers, cells, and modules. Each module of a solar PV plants withdraws and consumes approximately 1.1 gallons of water per m^2 of module area per year. The IC Sunshine project will include 45,896 m^2 of module area and will withdraw and consume approximately **50,405 gallons of freshwater** per year.

Looking at the entire life cycle of a PV panel, the production and processing of raw materials (upstream processes) and the manufacturing process used to make the panel consume significant amounts of electricity. The electricity used to produce silicon and to grown single crystals is generated primarily from thermoelectric power plants, which are water intensive (see Appendix B) (Kim, 2010). PV modules are not manufactured on Oahu; PV panel production, therefore, does not affect the local water supply for this project. But this water use will affect the global water supply.

The IC Sunshine project will include 28,533 silicon thin film modules. The electricity used in production and processing of silicon and the manufacturing process for these modules requires withdrawals of approximately **134.5 million gallons** of water.

Avoided CO_2 Emissions

The IC Sunshine Project will produce electricity without generating CO_2 emissions. In order to understand exactly how significant this is, the study compares these savings to what would have been generated by the local electricity grid and also by an equivalent size natural gas power plant.

CO_2	From the Grid		From a Natural Gas Facility	
Savings	**Year 1**	**Lifetime**[34]	**Year 1**	**Lifetime**[35]
Emissions (lbs)	16,807,926	314,715,561	10,528,260	197,133,612
Equiv. cars[36]	1,467	27,486	919	17,217
Costs ($)	$168,079	$3,147,156	$105,283	$1,971,336

From the Grid

Given the specific generation mix of fuel for the HIOA sub-region and required pollution controls, CO_2 emissions from the grid in HIOA occur at the rate of 1,811.98 lb/MWh[37] of generated electricity (U.S. EPA, 2008b). This rate is significantly higher than other regions of the country largely due to the state's high reliance on petroleum for much of the electricity generation. The IC Sunshine project is estimated to produce 9,276 MWh of electricity in the first year of production. Thus, IC Sunshine Project will **avoid 16,807,926 lbs** of CO_2 emissions in the first year of production that would otherwise have been emitted from the grid, which is equivalent to taking 1,467 cars off the road for one year. Recent estimates for short term and long term carbon prices have ranged from $10-$47 per ton of CO_2e (Capoor & Ambrosi, 2009). Assuming a price of $20 per ton of CO_2, the IC Sunshine project will save **$168,079** in CO_2 allowances that would have otherwise been purchased in the first year. Over a 20-year period (the life of the plant – assuming a 0.7 percent annual production degradation), this will prevent 314,715,561 lbs of CO_2 emissions and $3,147,156 in avoided emissions permitting costs.[38] If the U.S. adopts legislation to place a price on carbon, the avoided CO_2 from solar electricity generation will become more valuable since the price of carbon would likely rise over time.

From a Natural Gas Facility

According to the EPA, a natural gas generation facility will emit 1,135 lbs of CO_2 per MWh of electricity generated (U.S. EPA, 2007a). On average, a PV facility the size of IC Sunshine would **avoid 10,528,260 lbs of CO_2** emissions in its first year of operation; at an average cost of $20/ton CO_2 emitted, this would save **$105,283** in avoided CO_2 permits in the first year of production. Over the 20-year life of the PV plant (assuming a 0.7 percent annual degradation factor), the solar facility could be expected to avoid 197,133,612 lbs of CO_2 emissions. At an average cost of $20/ton CO_2, IC Sunshine could be expected to save $1,971,336 in avoided permit costs over the 20-year life of the PV facility.[39]

Avoided NO_X Emissions

The IC Sunshine Project will produce electricity without generating NO_X emissions. In order to understand exactly how significant this is, the study compares these savings to what would have been generated by the local electricity grid and also by an equivalent size natural gas power plant.

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[34] Assuming a 0.7% annual degradation factor

[35] Assuming a 0.7% annual degradation factor

[36] Equivalent cars refers to the equivalent number of cars removed from the road based on EPA reported U.S. transportation averages.

[37] The emissions factor of 1,811.98 lbs CO_2 per MWh is an average for natural gas plants in the HIOA sub-region. This factor is not specific to a NGCC plant because reliable averages for NGCC are not currently available.

[38] Assuming a constant $20/lb CO_2 with no discounting

[39] Assuming a constant $20/lb CO_2 with no discounting

NO_X	**From the Grid**		**From a Natural Gas Facility**	
Savings	**Annually**	**Lifetime[40]**	**Annually**	**Lifetime[41]**
Emissions (lbs)	24,006	449,499	15,769	295,266
Equiv. cars[42]	628	11,767	413	7,729
Costs ($)	$13,203	$247,255	$8,673	$162,396

From the Grid

Given the specific generation mix of fuel for the HIOA sub-region and required pollution controls, NO_X emissions from the grid in HIOA occur at the rate of 2.588 lb/MWh[43] of generated electricity (U.S. EPA, 2008b). The IC Sunshine project is estimated to produce 9,276 MWh of electricity in the first year of production. Thus, IC Sunshine Project will **avoid 24,006 lbs** of NO_X emissions in the first year of production. At a price of $1,100/ton[44] of NO_X, this will **save $13,203** in NO_X allowances that would have otherwise been purchased. Over a 20-year time period (the life of the plant – assuming 0.7 percent annual production degradation), this will avoid 449,499 lbs of NO_X emissions and $247,255[45] in emissions permitting cost.

From a Natural Gas Facility

According to the EPA, a natural gas generation facility will emit 1.7 lbs of NO_X per MWh of electricity generated (U.S. EPA, 2007a), although this number varies across the country depending on various required NO_X emissions controls. On average, a PV facility the size of IC Sunshine would **avoid 15,769 lbs of NO_X** emissions in its first year of operation; at an average cost of $1,100/ton NO_X, this would save **$8,673** in avoided NO_X permits in the first year of production. Over the 20-year life of the PV plant (assuming a 0.7 percent annual degradation factor), the solar facility could be expected to avoid **295,266 lbs** of NO_X emissions. At an average cost of $1,100/ton NO_X, IC Sunshine could be expected to save **$162,396** in avoided permit costs over the 20-year life of the PV facility.[46]

Health Impacts to the Community

Because Hawaii is an island state with very localized climates and weather patterns (Tradewind Creations LLC, 2010), the discussion of human health impacts is not relevant to power plant construction here. Winds from Hawaii blow east and east-northeast, carrying local air pollution in that direction. Hawaii is known to have some of the cleanest air in the nation, and the entire state has only one air quality measurement station for ozone. Hawaii does not contain any nonattainment areas for ozone or particulate matter, and human health impacts of emissions from sources other than volcanic eruptions

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[40] Assuming a 0.7% annual degradation factor

[41] Assuming a 0.7% annual degradation factor

[42] Equivalent cars refers to the equivalent number of cars removed from the road based on EPA reported U.S. transportation averages.

[43] The emissions factor of 2.588 lbs NO_X per MWh is an average for natural gas plants in the HIOA sub-region. This factor is not specific to a NGCC plant because reliable averages for NGCC are not currently available.

[44] This is the EPA's projected price of NO_X allowances for 2010. Source: Beth Murray – Clean Air Markets Division – May 2009.

[45] Assuming a constant $600/lb NO_X with no discounting

[46] Assuming a constant $600/lb NO_X with no discounting

have not been identified here (HI DOH, 2010). Thus, due to the isolated nature of the project location, health impacts from this PV project will be negligible to the immediate local community.

Job Creation

NREL's JEDI model forecasts that the IC Sunshine project will generate **74 jobs during its construction and installation phase**. This includes **18 direct construction and installation** jobs and **17 direct engineering, design and other professional service jobs** associated with project development. **28 indirect jobs** will be created from inter-industry purchases resulting from direct final demand (i.e. spending on materials and PV equipment and other purchases of goods and offsite services). Lastly the JEDI model forecasts that **11 induced jobs** will come about because of this project. Producing the same electricity from a natural gas plant would create 5 construction and installation jobs and ½ of a operations and maintenance job.

In total, these jobs will generate approximately $3.5 million in pre-tax earnings and total economic output of $7.2 million. No new jobs are created for ongoing maintenance and operations. However, the project yields a positive impact through estimated annual earnings of $66,800 and economic output of $153,900. In addition to the direct, indirect and induced impacts from this project the town of Kapolei, Hawaii will benefit from $189,337 in local property taxes.

Local Economic Impacts - Summary Results

	Jobs	Earnings	Output
During construction and installation period		**$000 (2008)**	**$000 (2008)**
Project Development and Onsite Labor Impacts	34	$2,034.8	$2,942.2
Construction and Installation Labor	18	$1,396.7	
Construction and Installation Related Services	17	$638.0	
Module and Supply Chain Impacts	28	$1,037.2	$2,850.6
Induced Impacts	11	$445.8	$1,406.7
Total Impacts	**74**	**$3,517.8**	**$7,199.5**
		Annual	**Annual**
	Annual	**Earnings**	**Output**
During operating years	**Jobs**	**$000 (2008)**	**$000 (2008)**
Onsite Labor Impacts			
PV Project Labor Only	0	$25.5	$25.5
Local Revenue and Supply Chain Impacts	0	$10.5	$31.1
Induced Impacts	1	$30.8	$97.2
Total Impacts	**1**	**$66.8**	**$153.9**

Notes: Earnings and Output values are thousands of dollars in year 2008 dollars. Construction and operating period jobs are full-time equivalent for one year (1 FTE = 2,080 hours). Economic impacts "During operating years" represent impacts that occur from system/plant operations/expenditures. Totals may not add up due to independent rounding.

Hi Desert Solar Project

The Hi Desert Solar PV Project under development by Axio Power is a 10 MW solar PV project located on 148 acres of land that was partially used for chicken farming and was partly barren near the town of Sunfair, California. Construction is scheduled to be completed in the second quarter of 2012. Using 49,565 Canadian Solar poly-crystalline PV panels, the project will generate 22,331 MWh of electricity per year without drawing significant amounts of water from the water table and while generating new tax revenue from the sales of electricity. It will also avoid NO_X and CO_2 emissions, prevent health problems related to NO_X emissions in the local community, and bring new jobs to the area.

The Hi Desert project is located in the CAMX sub-region as defined by the EPA. Each particular region is characterized by a unique fuel mix and required pollution controls, resulting in different emissions factors for different regions of the grid. The CAMX sub-region generation mix is comprised of: 11.9 percent coal, 42.3 percent natural gas, 17.7 percent hydropower, 16.5 percent nuclear, with the remaining 7 percent coming from a mix of geothermal, oil, solar, and wind.

Water Use

Water resources play an important role in the operation of a thermoelectric power plant (i.e., a power plant that uses coal, natural gas, oil, or nuclear fuel source). Approximately 99 percent of thermoelectric power plants in the U.S. rely on local saline or freshwater sources to provide cooling water used to condense the exhaust steam from the turbine-generator (NETL, 2009). Although power plants do not consume all of the water withdrawn from the water source, their operation depends on reliable access to a local water supply.

Water resources in the state of California are highly variable. The primary source of California's water supply is precipitation, which varies according to the climate, landform, season, and year. Moreover, the quantity, timing, and place of water demanded from the state's water users (agriculture, ecosystem, urban, etc.) is also variable. Over the past century, California met water demands, "primarily through an extensive network of water storage and conveyance facilities, groundwater development, and more recently, by improving efficiency." (CA DWR, 2009) Population growth and agriculture will continue to put demands on California's water supply in the future, especially during dry periods. Water conservation is thus an important concern in California.

The amount of local water needed to generate electricity using the Hi Desert project is significantly smaller than the amount of local water needed to generate electricity from the U.S. grid or from a NGCC plant of an equivalent size.

Local Water	**From the U.S. Grid**[47]		**From a NGCC plant**	
Savings	**Annually**	**Lifetime**[48]	**Annually**	**Lifetime**[49]
Withdrawals (gallons)	422.51 million	7.91 billion	6.36 million	118.9 million
Consumption (gallons)	15.22 million	284.9 million	5.94 million	111.1 million

Source: Appendix H

In order to generate electricity, the U.S. grid withdraws approximately 18,924 gallons per MWh of production and consumes approximately 686 gallons per MWh. A NGCC plant[50] withdraws approximately 289 gallons per MWh and consumes 270 gallons per MWh. The Hi Desert project is estimated to produce 22,331 MWh of electricity in the first year of production. If this electricity were generated by the U.S. grid it would withdraw 422.60 million gallons and consume 15.31 million gallons of water. If this electricity were generated at a NGCC plant it would withdraw 6.44 gallons and consume 6.03 gallons.

The operation of PV technologies requires water, which is used to clean and cool the wafers, cells, and modules. Each module of a solar PV plants withdraws and consumes approximately 1.1 gallons of water per m^2 of module area per year. The Hi Desert project will include 79,726 m^2 of module area and will withdraw and consume approximately 87,558 million gallons per year.

In the first year of production, the Hi Desert project will therefore **save 7.91 billion gallons** in water withdrawals and **284.9 million gallons** in water consumption when compared to the U.S. grid over the 20 year lifetime of the PV plant; and will **save 118.9 million gallons** in water withdrawals and **111.1 million gallons** in water consumption when compared to a NGCC plant over the 20 year lifetime of the PV plant.

Looking at the entire life cycle of a PV panel, the production and processing of raw materials (upstream processes) and the manufacturing process used to make the panel consume significant amounts of electricity. The electricity used to produce silicon and to grown single crystals is generated primarily from thermoelectric power plants, which are water intensive (see Appendix B) (Kim, 2010). PV modules are not manufactured near San Bernardino, CA; PV panel production, therefore, does not affect the local water supply for this project. But this water use will affect the global water supply.

The Hi Desert project will include 16,528 silicon thin film modules. The electricity used in production and processing of silicon and the module manufacturing process requires withdrawals of approximately **233.68 million gallons** of water. (Water consumption data for PV module manufacturing is not

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[47] See Appendix H for assumptions regarding the breakdown of U.S. net generation by fuel type and by cooling system type.

[48] Assuming a 0.7% annual degradation factor

[49] Assuming a 0.7% annual degradation factor

[50] This analysis assumes that most NGCC plants built after 2010 will use a wet recirculating cooling system. The use of closed-loop systems is likely to be more common in the future due to Clean Water Act provisions and public pressures. It is most likely that dry cooling will represent a small percentage of total combined cycle cooling (NETL 2009). The calculations included in this case studies uses withdrawal and consumption factors for a NGCC plant that uses a wet recirculating system.

available.) Looking at the global water supply, the water withdrawals over the lifetime of the PV plant would therefore *exceed* the withdrawals associated with the operation of a NGCC plant by **114.8 million gallons**.

Avoided CO_2 Emissions

The Hi Desert Project will produce electricity without generating CO_2 emissions. In order to understand exactly how significant this is, the study compares these savings to what would have been generated by the local electricity grid and also by an equivalent size natural gas power plant.

CO_2	**From the Grid**		**From a Natural Gas Facility**	
Savings	**Year 1**	**Lifetime**[51]	**Year 1**	**Lifetime**[52]
Emissions (lbs)	16,170,324	302,776,937	25,345,685	474,578,556
Equiv. cars[53]	1,412	26,443	2,214	41,448
Costs ($)	$161,703	$3,027,769	$253,457	$4,745,786

From the Grid

Given the specific generation mix of fuel for the CAMX sub-region and required pollution controls, NO_X emissions from the grid in CAMX occur at the rate of 724.12 lb/MWh[54] of generated electricity (U.S. EPA, 2008b). This rate is much lower than most other areas of the country due to California's use of lower carbon intensity fuel sources such as hydropower, natural gas and nuclear for nearly 80 percent of its electricity generation. The Hi Desert project is estimated to produce 22,331 MWh/yr of electricity in its first year of production. Thus, Hi Desert Project will **avoid 16,170,324 lbs** of CO_2 emissions in the first year of production, which is equivalent to removing 1,412 cars from the road for one year. Recent estimates for short term and long term carbon prices have ranged from \$10-\$47 per ton of CO_2e (Capoor & Ambrosi, 2009). Assuming a price of \$20 per ton of CO_2, the Hi Desert project will save **$161,703** in CO_2 allowances that would have otherwise been purchased in the first year. Over a 20-year period (the life of the plant – assuming a 0.7 percent annual production degradation), this will avoid **302,776,937 lbs** of CO_2 emissions and **$3,027,769** in emissions permitting cost.[55] If the U.S. adopts legislation to place a price on carbon, the avoided CO_2 from solar electricity generation would become more valuable because the price of carbon would likely rise over time.

From a Natural Gas Facility

According to the EPA, a natural gas generation facility will emit 1135 lbs of CO_2 per MWh of electricity generated (U.S. EPA, 2007a). On average, a PV facility the size of Hi Desert would **avoid 25,345,685 lbs of CO_2** emissions in its first year of operation; at an average cost of \$20/ton CO_2, this would save **$253,457** in avoided CO_2 permits in the first year of production. Over the 20-year life of the PV plant

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[51] Assuming a 0.7% annual degradation factor

[52] Assuming a 0.7% annual degradation factor

[53] Equivalent cars refers to the equivalent number of cars removed from the road based on EPA reported U.S. transportation averages.

[54] The emissions factor of 724.12 lbs CO_2 per MWh is an average for natural gas plants in the CAMX sub-region. This factor is not specific to a NGCC plant because reliable averages for NGCC are not currently available.

[55] Assuming a constant \$20/lb CO_2 with no discounting

(assuming a 0.7 percent annual degradation factor), the solar facility could be expected to avoid **474,578,556 lbs** of CO_2 emissions. At an average cost of $20/ton CO_2, Hi Desert could be expected to save **$4,745,786** in avoided permit costs over the 20-year life of the PV facility.[56]

Avoided NO_X Emissions

The Hi Desert Project will produce electricity without generating NO_X emissions. In order to understand exactly how significant this is, the study compares these savings to what would have been generated by the local electricity grid and also by an equivalent size natural gas power plant.

NO_X	**From the Grid**		**From a Natural Gas Facility**	
Savings	**Year 1**	**Lifetime[57]**	**Year 1**	**Lifetime[58]**
Emissions (lbs)	13,794	258,279	37,963	710,823
Equiv. cars[59]	361	6,761	994	18,608
Costs ($)	$7,587	$142,054	$20,879	$390,952

From the Grid

Given the specific generation mix of fuel for the CAMX sub-region and required pollution controls, NO_X emissions from the grid in CAMX occur at the rate of 0.6177 lb/MWh[60] of generated electricity (U.S. EPA, 2008b). The Hi Desert project is estimated to produce 22,331 MWh/yr of electricity in its first year of production. Thus, the Hi Desert Project will **avoid 13,794 lbs** of NO_X emissions in the first year of production. At a price of $1,100/ton[61] of NO_X, in the first year, this will **save $7,587** NO_X allowance costs. Over a 20-year time period (the life of the plant – assuming 0.7 percent annual production degradation), this will avoid **258,279** lbs of NO_X emissions and **$142,054**[62] in emissions allowance purchases.

From a Natural Gas Facility

According to the EPA, a natural gas generation facility will emit 1.7 lbs of NO_X per MWh of electricity generated (U.S. EPA, 2007a), although this number varies across the country depending on various required NO_X emissions controls. On average, a PV facility the size of Hi Desert would **avoid 37,963 lbs of NO_X** emissions in its first year of production; at an average cost of $1,100/ton[63] of NO_X, this would **save $20,879** in avoided NO_X permits in the first year. Over the 20-year life of a PV plant (assuming 0.7 percent annual degradation), the solar facility could be expected to avoid **710,823 lbs** of NO_X emissions.

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[56] Assuming a constant $20/lb CO_2 with no discounting

[57] Assuming a 0.7% annual degradation factor

[58] Assuming a 0.7% annual degradation factor

[59] Equivalent cars refers to the equivalent number of cars removed from the road based on EPA reported U.S. transportation averages.

[60] The emissions factor of 0.6177 lbs NO_X per MWh is an average for natural gas plants in the CAMX sub-region. This factor is not specific to a NGCC plant because reliable averages for NGCC are not currently available.

[61] This is the EPA's projected price of NO_X allowances for 2010. Source: Beth Murray – Clean Air Markets Division – May 2009.

[62] Assuming a constant $600/lb NO_X with no discounting

[63] This is the EPA's projected price of NO_X allowances for 2010. Source: Beth Murray – Clean Air Markets Division – May 2009.

At an average cost of \$1,100/ton NO_X, Hi Desert could be expected to save **\$390,952** in avoided permit costs over the 20-year life of the PV facility.

Health Impacts to the Community

The Hi Desert site is located in San Bernardino County, CA with prevailing winds moving emissions toward the west and northwest, into the Las Vegas valley or areas with low population density. San Bernardino County is located downwind of the Los Angeles metropolitan area and feels the effect of that area's pollution. The Hi Desert site is located within a nonattainment area for the eight-hour ozone standard and near a nonattainment area for $PM_{2.5}$ (CA ARB, 2010). The American Lung Association's State of the Air Report found that in 2006-2008, San Bernardino County had the most days with ozone concentrations above healthy levels of any U.S. county. Also, 8.6 percent of San Bernardino county residents report having pediatric or adult asthma (American Lung Association, 2010). The California Healthcare Foundation estimates that in 2007, 10.8 percent of children in San Bernardino had active asthma (California Healthcare Foundation, 2010). Introducing additional NO_X emissions into this area would contribute to this existing air quality problem.

Job Creation

NREL's JEDI model forecasts that the Hi Desert project will generate **504 jobs during its construction and installation phase**. This includes **116 direct construction and installation** jobs and **35 direct engineering, design and other professional service jobs** associated with project development. **241 indirect jobs** will be created from inter-industry purchases resulting from direct final demand (i.e. spending on materials and PV equipment and other purchases of goods and offsite services). Lastly the JEDI model forecasts that **113 induced jobs** will come about because of this project. Producing the same electricity from a natural gas plant would create 10 construction and installation jobs and 1 operations and maintenance job.

In total, these jobs will generate approximately \$33.5 million in pre-tax earnings and total economic output of \$76.5 million. Virtually no new jobs are created for ongoing maintenance and operations. However, the project yields positive impact through estimated annual earnings of \$63,900 and economic output of \$91,300.

Local Economic Impacts - Summary Results

During construction and installation period	Jobs	Earnings $000 (2010)	Output $000 (2010)
Project Development and Onsite Labor Impacts	151	$11,013.4	$13,591.2
Construction and Installation Labor	116	$9,126.8	
Construction and Installation Related Services	35	$1,886.6	
Module and Supply Chain Impacts	241	$16,386.5	$44,042.2
Induced Impacts	113	$6,132.4	$18,900.5
Total Impacts	**504**	**$33,532.3**	**$76,534.0**

During operating years	Annual Jobs	Annual Earnings $000 (2010)	Annual Output $000 (2010)
Onsite Labor Impacts			
PV Project Labor Only	0.0	$51.1	$51.1
Local Revenue and Supply Chain Impacts	0.1	$7.4	$23.5
Induced Impacts	0.1	$5.4	$16.7
Total Impacts	**0.2**	**$63.9**	**$91.3**

Notes: Earnings and Output values are thousands of dollars in year 2010 dollars. Construction and operating period jobs are full-time equivalent for one year (1 FTE = 2,080 hours). Economic impacts "During operating years" represent impacts that occur from system/plant operations/expenditures. Totals may not add up due to independent rounding.

Case Study Conclusions

As the report identified, the relative importance of these impacts depends on the size, geography, and regulatory incentives of the project site. At the same time, some benefits are common to projects anywhere in the U.S. All sites create benefits from reduced acid rain due to avoided NO_X emissions and avoided water consumption that would deplete limited sources of fresh water. Also, the avoided CO_2 emissions have real environmental impacts and contribute to an evolving electricity infrastructure that can support alternative energy. If greenhouse gas emissions are limited nationally, the avoided emissions will also have monetary benefits at any U.S. project site.

The case studies illustrated how some of these impacts can vary widely across project sites. At Greenfield, the avoided emissions and their health benefits have the largest impact on the community around the project site. The high concentration of NO_X already in the atmosphere around Greenfield makes avoided NO_X emissions valuable and the health benefits from avoided emissions real. Additionally, because the Regional Greenhouse Gas Initiative operates in Massachusetts, avoided CO_2 emissions will have real monetary benefits in the short term.

At the IC Sunshine site in Hawaii, the unique generation mix and isolated geography bring solar PV near grid parity with existing electricity. Its location in the Pacific Ocean far from other population centers and with plentiful supplies of ocean water mean that few benefits come from avoided NO_X emissions and avoided water consumption. The job creation benefits of solar PV at this site dominate the benefits of this project over a gas-fired power plant.

The Hi Desert project avoids water consumption in a region with an uncertain water supply and avoids NO_X emissions in a nonattainment zone. Fresh water is an expensive and fickle resource in southern California, and a PV project's lack of reliance on a water supply is a valuable benefit here. Because this region exceeds EPA standards for NO_X emissions, avoided emissions also create a benefit because additional state action will not be required to compensate for the impacts of NO_X that a gas-fired plant would emit. California is also implementing a statewide greenhouse gas reduction program, and avoided CO_2 emissions will have quantifiable monetary benefits starting in 2012.

Across project sites, examining the impacts of these benefits yielded information that a traditional project analysis would miss. Project developers can use an analysis of these ancillary impacts in project proposals to illustrate the full impact of their projects to specific sites, and policymakers in different regions can use them to create a holistic analysis of power generation projects. The case studies demonstrate the value of analyzing these ancillary impacts of solar PV development.

Conclusion

This report synthesizes knowledge from various disciplines related to economics, environmental science, epidemiology, health sciences, and policy to determine and explain the most significant and tangible benefits of solar power in relation to its most common competitor, natural gas-fired power plants. The most significant relative social and environmental benefits of solar power for policymakers and consumers are:

- Near elimination of water consumption;
- Local job creation and economic development;
- Avoidance of NO_X emissions and the resulting environmental impacts
- Prevented human health impacts of NO_X emissions; and
- Avoidance of CO_2 emissions, including the resulting environmental impact and uncertainty around potential greenhouse gas regulation.

These key ancillary benefits of solar are particularly relevant to the individuals and institutions who set policies that may encourage or hinder the development of certain electricity sources, individuals near project sites, and electricity consumers. As demonstrated in the three case studies, the amount of each benefit depends on a specific project's size and geographic location. Although these impacts are outside the scope of most traditional project analyses conducted by developers, their inclusion provides a more comprehensive picture of the value of a project to a community or electricity market. For these reasons, policymakers in a community or state may consider incentives for solar development that compensate for the cost differential between solar and fossil fuel generation because they find that the overall benefits of solar will collectively outweigh the cost of incentives.

Case Study Results

The case studies illustrated both impacts that are common to any solar PV project in the U.S. and impacts that vary based on project site. Reduced water consumption, avoided NO_X emissions, and avoided CO_2 emissions create benefits across all project sites. The job creation and community impact of solar PV projects depend on the sourcing of materials used for the project as well as state or local tax incentives to solar developers that impact the tax revenues a project generates. Human health benefits from avoided NO_X emissions vary depending on the weather patterns around a site and the characteristics of populations and conditions downwind of sites. The value of water consumption savings varies based on the scarcity of fresh water in the present and future at project sites.

The five ancillary impacts discussed in this study proved relevant at all three case study sites. This result implies that they will be pertinent to a variety of project sites throughout the U.S. The variance in the relative importance of impacts also suggests that solar project developers and policymakers should focus on the impacts that are most relevant for their sites and regions. This study provides the background needed to assess sites for the relative importance of different impacts and to measure and communicate these impacts to stakeholders.

Future Research Opportunities

Under the current and likely future policy environment and resource constraints, the impacts identified in this study were the most relevant to the industry experts and stakeholders interviewed. The benefits analyzed in this report are by no means exhaustive and were chosen based on the significance of the impacts and applicability to projects of various sizes in various climates and geographies. Researchers in different geographic areas with unique natural resource constraints may find other factors more important when comparing solar with its local competitor. In addition some benefits will be more applicable to certain regions in the U.S. than others. In the western U.S., for example, where water is scarce, the reduction in water use from solar has real financial and regulatory benefits. In the Midwest and East where acid rain and poor air quality are historical problems, minimizing NO_X emissions has monetary value and a notable human health impact. Future research is needed to identify governmental policies that quantify these benefits in different regions—allowing solar to compete with conventional generation based on a broader picture of costs and benefits—and project evaluation procedures that fully account for impacts that are difficult to predict and quantify.

Further research into benefits beyond the scope of this report could provide a more complete analysis of solar PV's relative benefits. In particular, the economic and environmental impacts of developing a brownfield or disturbed plot of land with solar PV and the land use impacts of PV relative to other uses such as agriculture or natural carbon sequestration could reveal costs and benefits not captured in current literature.

This report hopes to provide a starting point for planning for power generation projects based on a more complete understanding of their costs and benefits than a traditional analysis of their easily quantifiable costs and benefits would allow. The five ancillary impacts discussed in this report are applicable to projects and regional planning efforts throughout the U.S., and they will continue to be relevant under changing climate conditions and regulatory scenarios. Given the uncertainty related to climate change and the availability of fossil fuels, this more holistic approach to planning and project evaluation will be critical for reliably meeting future electricity needs in the U.S.

References

Abbey et al., D. (1999). Long-term inhalable particles and other air pollutants related to mortality in nonsmokers. *American Journal of Respiratory and Critical Care Medicine , 159*, 373-382.

ABT Associates, Inc. (2004). *Power Plant Emissions: Particulate Matter Related Health Damages and the Benefits of Alternative Emission Reduction Scenarios.* Boston: Clean Air Task Force.

AERMOD Implementation Workgroup. (2009, March 19). *Preferred/Recommended Models l TTN: Support Center for Regulatory Atmospheric Modeling.* Retrieved July 10, 2010, from U.S. Environmental Protection Agency: http://www.epa.gov/cgi-bin/epalink?logname=allsearch&referrer=aermod%20implementation%20guide|3|All&target=http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_implmtn_guide_19March2009.pdf

Akimoto, H. (2003). Global Air Quality and Pollution. *Science , 302*, 1716-1719.

Allen, J. (2002, April 19). *The Ozone We Breathe*. (N. E. Observatory, Producer) Retrieved September 9, 2010, from National Aeronautics and Space Administration, Earth Observatory: http://earthobservatory.nasa.gov/Features/OzoneWeBreathe/ozone_we_breathe.php

American Lung Association. (2010). *State of the Air 2010- Key Findings.* Washington, D.C.: American Lung Association.

Arizona Water Institute. (2007). *Fact Sheet: The Water Costs of Electricity in Arizona.* Retrieved July 10, 2010, from Arizona Water Institute: http://www.azwaterinstitute.org/media/Pasqualetti%20fact%20sheet

—. (2009). *Water and Energy Sustainability and Rapid Growth and Climate Change in the Arizona-Sonora Border Region.* Retrieved July 10, 2010, from Arizona Water Institute: http://www.azwaterinstitute.org/media/Scott%20final%20report%2008

Associated Press. (2002, August 2). *Power plant shelved after water use denied*. Retrieved July 26, 2010, from Seattle Post - Intelligencer: http://www.seattlepi.com/local/81058_water02.shtml

Beeson, W., Abbey, D., & Knutsen, S. (1998). Long-term concentrations of ambient air pollutants and incident lung cancer in California adults: results from the AHSMOG study. *Environmental Health Perspective , 106* (12), 813-823.

Borenstein, S. (2008, July 11). An American Life Worth Less Today. *Associated Press* , p. 1.

Bowman, C. T. (1992). Control of Combustion Generated Nitrogen Oxide Emissions: Technology Driven by Regulation. *Twenty Fourth Symposium (International) on Combustion* (pp. 859-878). Stanford: The Combustion Institute.

Brunekreef, B. (1999, February 1). All But Quiet on the Particulate Front. *American Journal of Respiratory and Critical Care Medicine , 159* (2), pp. 354-356.

California Air Resources Board (CA ARB). (2010, March 25). *Area Designation Maps/ State and National*. Retrieved November 5, 2010, from California Air Resources Board, Standards and Designations: http://www.arb.ca.gov/desig/adm/adm.htm

California Department of Water Resources (CA DWR). (2009). *California Water Plan - Update 2009.* Retrieved 2010 18, November, from California Department of Water Resources, Integrated Water Management: http://www.waterplan.water.ca.gov/cwpu2009/

California Energy Commission. (2005). *California's Water - Energy Relationship.* Retrieved July 10, 2010, from California Energy Commission: http://www.energy.ca.gov/2005publications/CEC-700-2005-011/CEC-700-2005-011-SF.PDF

California Healthcare Foundation. (2010, January 1). *Children with Active Asthma, 2007*. Retrieved November 5, 2010, from California Healthcare Foundation Data: http://data.chcf.org/chronic-conditions/data/profile/show.aspx?ind=30&dtm=31&tf=2&loc=34

California Public Interest Research Group (CALPIRG). (2002). *Renewables Work: Job Growth from Renewable Energy Development in California.* Retrieved August 20, 2010, from Environmental California, Energy Reports: http://www.environmentcalifornia.org/reports/energy/energy-program-reports/renewables-work-job-growth-from-renewable-energy-development-in-california3

Capoor, K., & Ambrosi, P. (2009). *State and Trends of the Carbon Market 2009.* Washington DC: The World Bank.

Clean Air Task Force and the Land and Water Fund of the Rockies. (2003). *The Last Straw: Water Use by Power Plants in the Arid West.* Retrieved June 6, 2010, from Clean Air Task Force: Publications: http://www.catf.us/resources/publications/files/The_Last_Straw.pdf

Dennen, B., Larson, D., Lee, C., Lee, J., Tellinghuisen, S. (2007). *California's Energy-Water Nexus: Water Use in Electricity Generation.* Donald Bren School of Environmental Science & Management, University of California, Santa Barbara.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E. (1993). An Association between Air Pollution and Mortality in Six U.S. Cities. *New England Journal of Medicine , 329*, 1753-1759.

Dockery, D.W., Speizer, F.E., Stram, D.O., Ware, J.H., Spengler, J.D., Ferris, B.D. (1989). Effects of inhalable particles on respiratory health of children. *American Review of Respiratory Disease , 139* (3), 587-594.

Dockery, D. W., & Spengler, J. D. (1981). Indoor-outdoor relationships of respirable sulfates and particles. *Atmospheric Environment* (15), 335-343.

EcoSecurities. (2009). *Assigning Carbon Price Estimates to Alternative Policy Scenarios.* Portland, Oregon: EcoSecurities.

Electric Power Research Institute (EPRI). (2002). *Water & Sustainability (Volume 3): U.S. Water Consumption for Power Production - The Next Half Century.* Palo Alto, CA: Electric Power Research Institute.

—. (2003). *A Survey of Water Use and Sustainability in the United States with a Focus on Power Generation.* Retrieved June 12, 2010, from Electric Power Research Institute: http://my.epri.com/portal/server.pt?

Feldman, D., Slough, A., & Garrett, G. (2008). *Freshwater Availability and Constraints on Thermoelectric Power Generation in the Southeast U.S.* Retrieved July 10, 2010, from Southern States Energy Board: http://www.sseb.org/files/freshwater-availability-thermoelectric-power.pdf

Fthenakis, V., & Kim, H. (2010). Life-cycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews , 14*, 2039-2048.

Fthenakis, V., Kim, H., & Alsema, E. (2008). Emissions from Photovoltaic Life Cycles. *Environmental Science and Technology* , 2168-2174.

Gardner, D. (1980). Influence of Exposure Patterns of Nitrogen Dioxide on Susceptibility to Infectious Respiratory Disease. In S. See, *Nitrogen Oxides and Their Effects on Health* (pp. 267-288). Ann Arbor, MI, USA: Ann Arbor Science Publishers, Inc.

Gilliland, F. D. (2001). The Effects of Ambient Air Pollution on School Absenteeism Due to Respiratory Illness. *Epidemiology , 12*, 43-54.

Guswhenta Developments. (2007). *Combined Cycle Power*. Retrieved September 5, 2010, from http://www.guswhenta.com/eaglesnest/combined_cycle.html

Hart, G. (2009a). *ICAP Energy Environmental Markets Brief.* Sugar Land, TX: ICAP.

—. (2009b). *The Roller Coaster Ride of the* NO_X *Allowance Market.* Sugarland: ICAP.

Hawaiin Electric Company (HECO). (n.d.). *About HECO*. Retrieved November 16, 2010, from http://www.heco.com/portal/site/heco/

Hawaii Department of Health (HI DOH). (2010). *State of Hawaii Annual Summary 2009 Air Quality Data.* Retrieved November 6, 2010, from Hawaii Department of Health, Environmental Health: http://hawaii.gov/health/environmental/air/cab/cabmaps/pdf/2009_aqbook.pdf

ICF International. (2007). *The HAPEM User's Guide, Hazardous Air Pollution Exposure Model Version 6.* for U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Washington, D.C.: ICF International.

Idaho Code. (2006). *Coal Fire Power Plant - Moratorium* . Chapter 1, Title 39, Sections 39-124 and 39-125. http://www3.idaho.gov/oasis/2006/H0791.html.

International Energy Administration (IEA). (2006). *9.1 Reaction Chemistry of* NO_X. Retrieved July 18, 2010, from International Energy Agency, NO_X Emissions and Control: http://www.iea-coal.org.uk/catalogues/coalonline/81423/6029/html/6029_143.html

Interngovernmental Panel on Climate Change (IPCC). (2007). *Summary for Policymakers.* Retrieved July 20, 2010, from Intergovernmental Panel on Climate Change, IPCC Fourth Assessment Report: Climate Change 2007: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spm.html

—. (2007). *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* New York: Cambridge University Press.

Kim, H. C. (2010, November 22). RE: LCA question for master's project. Email to the author.

King, C., Duncan, I., & Webber, M. (2008). *Water Demand and Projections for Power Generation in Texas.* Retrieved July 10, 2010, from Texas Water Development Board: http://www.twdb.state.tx.us/RWPG/rpgm_rpts/0704830756ThermoelectricWaterProjection.pdf

Massachusetts Department of Environmental Protection (MA DEP). (2008). *Final Massachusetts State Implementation Plan to Demonstrate Attainment of NAAQS for Ozone.* Boston: Massachusetts Department of Environmental Protection.

Massachusetts Department of Public Health (MA DPH). (2009). *Burden of Asthma in Massachusetts.* MA DPH, Asthma Prevention and Control Program. Boston: Massachusetts Department of Public Health.

McDonnell, W.F., Abbey, D.E., Nishino, N., Lebowitz, M.D. (1999). Long-term ambient ozone concentration and incidence of asthma in nonsmoking adults: the AHSMOG Study. *Environmental Research , 80*, 110-121.

McNatt, L. (2010, February 5). *Surry Board OKs Coal Power Plant*. Retrieved 15 2010, October, from The Virginian-Pilot: http://hamptonroads.com/2010/02/surry-board-oks-coal-power-plant

National Energy Technology Laboratory (NETL). (2009, September). *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements.* Retrieved June 6, 2010, from National Energy Technology Laboratory: Energy Analysis: http://www.netl.doe.gov/energy-analyses/refshelf/detail.asp?pubID=278

National Institute of Environmental Health Sciences (NIEHS). (2001). *Ozone Alert.* Retrieved August 31, 2010, from National Institute of Environmental Health Sciences - National Institutes of Health, Educational Resources: http://www.niehs.nih.gov/health/scied/resources/index.cfm

National Oceanic and Atmospheric Administration (NOAA). (2010). *Trends in Atmospheric Carbon Dioxide*. Retrieved July 21, 2010, from National Oceanic & Atmospheric Administration, Earth System Monitoring Laboratory, Global Monitoring Division: http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo

National Renewable Energy Laboratory (NREL). (2000). *Life Cycle Analysis of a Natural Gas Combined-Cycle Power Generation System.* Retrieved October 10, 2010, from National Renewable Energy Laboratory: http://www.nrel.gov/docs/fy00osti/27715.pdf

—. (2002). *Fuel from the Sky: Solar Power's Potential for Western Energy Supply.* Retrieved November 15, 2010, from National Energy Renewable Laboratory: Concentration Solar Power Research: http://www.nrel.gov/csp/pdfs/32160.pdf

—. (2008). *Photovoltaic Solar Resource: United States and Germany.* Retrieved September 13, 2010, from Solar Energy Industry Association: http://www.seia.org/galleries/default-file/PVMap_USandGermany.pdf

Oberdorster, G., Oberdorster, E., & Oberdorster, J. (2005). Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles. *Environmental Health Perspectives , 113*, 823-839.

Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association , 287* (9), 1132-1141.

Pope, C. A., & Dockery, D. W. (2006). Health Effects of Fine Particulate Air Pollution: Lines That Connect. *Journal of the Air & Waste Management Association , 56*, 709-742.

Pope, C. (2000). Epidemiology of Fine Particulate Air Pollution and Human Health: Biologic Mechanisms and Who's at Risk? *Environmental Health Perspectives Supplements , 108* (S4), 713-723.

Renner, M. (2008, July 8). *Jobs in Renewable Energy Expanding*. Retrieved July 26, 2010, from WorldWatch Institute: http://www.worldwatch.org/node/5821#notes

Rizzo, A.A. (2010, March 4). Member of Board of Directors, American Lung Association. (S. E. Safety, Interviewer)

Rocky Mountain Mineral Law Foundation. (2002). *IDWR Decisions Based on Public Interest and Conservation Considerations.* Water Law Newsletter, Volume XXXV, Number 3.

Schwartz, J. (1994a, September 15). Air Pollution and Hospital Admissions for the Elderly in Birmingham, AL. *American Journal of Epidemiology , 139* (6), pp. 589-594.

—. (1994b, September 15). Air Pollution and Hospital Admissions for the Elderly in Detroit, MI. *American Journal of Respiratory and Critical Care Medicine , 150* (3), pp. 648-655.

—. (1994c, September 15). PM sub 10, Ozone, and Hospital Admissions for the Elderly in Minneapolis-St. Paul, Minnesota. *Archives of Environmental Health , 49* (5).

Solar Energy Inudstries Association (SEIA). (2010). *US Solar Industry Year in Review 2009.* Retrieved September 13, 2010, from Solar Energy Industries Association: News, Research & Multimedia: http://www.seia.org/cs/news_research_and_multimedia/news_research_and_multimedia

Sillman, D. S. (2009, January 21). *Sillman: Ozone and Air Quality Modeling*. Retrieved July 17, 2010, from University of Michigan - personal pages: http://www-personal.umich.edu/~sillman/research.htm

Singh, V., & Fehrs, J. (2001). *The Work That Goes Into Renewable Energy.* Washington, DC: Renewable Energy Policy Project (REPP).

Sovacool, B., & Sovacool, K. (2009a). Identifying future electricity-water tradeoffs in the United States. *Energy Policy* , 3763-2773.

Sovacool, B., & Sovacool, K. (2009b). Preventing National Electricity-Water Crisis Areas in the United States. *Columbia Journal of Environmental Law , 34*, 333-393.

Stillwell, A., King, C., Webber, M., Duncan, I., & Hardberger, A. (2009). *Energy-Water Nexus in Texas.* Retrieved July 10, 2010, from Environmental Defense Fund: http://www.edf.org/documents/9479_Energy-WaterNexusinTexasApr2009.pdf

Synapse Energy. (2008). *Synapse 2008: CO2 Price Forecasts.* Cambridge, MA: Synapse Energy Economics Inc.

Tradewind Creations LLC. (2010, January 1). *Hawaii Weather and Climate Patterns*. Retrieved November 5, 2010, from Hawaii-Guide: http://www.hawaii-guide.com/index.php/content/posts/hawaii_weather_and_climate_patterns/P0/

U.S. Bureau of Labor Statistics (U.S. BLS). (2009, December 10). *Employment Projections: 2008-18 News Release.* Retrieved November 23, 2010, from U.S. Bureau of Labor Statistics: http://www.bls.gov/news.release/ecopro.htm

U.S. Department of Energy (U.S. DOE). (2005). *Solar Energy Technologies Program.* Retrieved September 8, 2010, from U.S. Department of Energy: Energy Efficiency & Renewable Energy: http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

U.S. Energy Information Agency (U.S. EIA). (1998). *Natural Gas Issues and Trends 1998.* Department of Energy, Energy Information Administration. Washington, D.C.: Energy Information Administration.

—. (2005). *EIA-767 Data Files. Annual Steam-Electric Plant Operation and Design Data.* Retrieved November 7, 2010, from U.S. Energy Information Administration, Electricity Database Files: http://www.eia.doe.gov/cneaf/electricity/page/eia767.html

—. (2009). *Annual Energy Review 2008.* Retrieved July 13, 2010, from U.S. Energy Information Agency, Annual Energy Review: http://www.eia.gov/FTPROOT/multifuel/038408.pdf

—. (2010a). *Annual Energy Outlook 2010.* Retrieved July 15, 2010, from Energy Information Agency: Forecasts & Analysis: http://www.eia.doe.gov/oiaf/aeo/index.html

—. (2010b, April 9). *Electricity Market Module.* Retrieved October 15, 2010, from U.S. Energy Information Agency: Assumptions to the Annual Energy Outlook 2010: http://www.eia.doe.gov/oiaf/aeo/assumption/electricity.html

—. (2010c, August 11). *Net Generation by Energy Source: Total (All Sectors).* Retrieved September 13, 2010, from Energy Information Agency: Electric Power Monthly: http://www.eia.doe.gov/cneaf/electricity/epm/table1_1.html

U.S. Environmental Protection Agency (U.S. EPA). (1998). *Emissions Factors & AP 42.* Retrieved July 15, 2010, from U.S. Environmental Protection Agency, Technology Transfer Network, Clearinghouse for Emissions Inventories and Emissions Factors: http://www.epa.gov/ttn/chief/ap42/ch01/index.html

—. (1999a). *Nitrogen Oxides (NO_X), Why and How They are Controlled.* Retrieved June 28, 2010, from U.S. Environmental Protection Agency, Clean Air Technology Center: http://www.epa.gov/ttn/catc/dir1/fnoxdoc.pdf

—. (1999b). *Smog-Who Does it Hurt?* Washington, DC: U.S. Environmental Protection Agency, Air and Radiation.

—. (2000). *Guidelines for Preparing Economic Analyses.* U.S. Environmental Protection Agency. Washington, D.C.: U.S. EPA.

—. (2003). *NO_X Budget Program 1999-2002 Progress Report.* Retrieved July 17, 2010, from Ozone Transport Commission, NO_X Budget Program: http://www.epa.gov/airmarkets/progsregs/nox/docs/otcreport.pdf

—. (2004). *Human Health and Environmental Effects of Emissions from Power Generation.* Retrieved July 27, 2010, from U.S. Environmental Protection Agency, Clean Air Market Programs: www.epa.gov/capandtrade/documents/power.pdf

—. (2005). *Revision to Guideline on Air Quality Models.* U.S. Environmental Protection Agency. Washington, D.C.: Federal Register.

—. (2007a, December 28). *Air Emissions | Clean Energy*. Retrieved October 25, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html

—. (2007b, June 8). *Effects of Acid Rain*. Retrieved July 16, 2010, from U.S. Environmental Protection Agency, Acid Rain: http://www.epa.gov/acidrain/effects/index.html

—. (2007c, May 22). *Human Exposure Modeling: Hazardous Air Pollutant Exposure Model (HAPEM)*. Retrieved September 21, 2010, from U.S. Environmental Protection Agency, Technology Transfer Network: http://www.epa.gov/ttn/fera/human_hapem.html

—. (2008a, August 29). *Cleaning Up Commonly Found Air Pollutants l Plain English Guide to The Clean Air Act*. Retrieved August 7, 2010, from U.S. Environmental Protection Agency: http://www.epa.gov/air/caa/peg/cleanup.html

—. (2008b). *eGRID2007 Version 1.1: Year 2005 Summary Tables.* Environmental Protection Agency.

—. (2008c, May 9). *Health and Environment l Ground-level Ozone*. Retrieved August 7, 2010, from U.S. Environmental Protection Agency: http://www.epa.gov/air/ozonepollution/health.html

—. (2009a). *2008 Highlights | NO_X Budget Trading Program 2008 Progress Reports*. Retrieved July 21, 2010, from http://www.epa.gov/airmarkets/progress/NBP_4.html

—. (2009b, December 17). *Acid Rain Program 2008 Progress Reports.* Retrieved July 15, 2010, from 2008 Highlights: http://www.epa.gov/airmarkets/progress/ARP_4.html

—. (2009c, December 17). *Air Pollutants Exposure Model*. Retrieved August 8, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/ttn/fera/human_apex.html

—. (2009d). EPA Analysis of Alternative SO2 and NO_X Caps for Senator Carper. 20-27. Washiongton, D.C., USA: U.S. Environmental Protection Agency.

—. (2009e, June 29). *Nitrogen Dioxide | Health*. Retrieved August 3, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/airquality/nitrogenoxides/health.html

—. (2009f, November 9). *Nitrogen Oxides*. Retrieved August 3, 2010, from U.S. Environmental Protection Agency, Air Emission Sources: http://www.epa.gov/air/emissions/nox.htm

—. (2009g, November 4). *Nitrogen Oxides | Air Emissions Sources*. Retrieved July 10, 2010, from U.S. Environmental Protection Agency, Air & Radiation: http://www.epa.gov/air/emissions/nox.htm

—. (2009h). *NO_X Budget Trading Program.* Retrieved July 17, 2010, from U.S. Environmental Protection Agency, NO_X Trading Programs: http://www.epa.gov/airmarkets/progsregs/nox/docs/NBPbasicinfo.pdf

—. (2009i, April 4). *NO_X Trading Programs | Programs and Regulations*. Retrieved July 20, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/airmarkets/progsregs/nox/index.html

—. (2010a, April 1). *Air Trends | Nitrogen Dioxide.* Retrieved July 20, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/airtrends/nitrogen.html

—. (2010b, January 7). *Basic Information | Ground Level Ozone*. Retrieved July 19, 2010, from U.S. Environmental Protection Agency, Air & Radiation: http://www.epa.gov/air/ozonepollution/basic.html

—. (2010c, June 24). *Clean Air Act*. Retrieved July 18, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/air/caa/

—. (2010d, July 9). *Clean Air Interstate Rule*. Retrieved November 21, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/cair/index.html

—. (2010e, September 2). *Environmental Benefits Mapping and Analysis Program (BenMAP)*. Retrieved September 20, 2010, from U.S. Environmental Protection Agency: http://www.epa.gov/air/benmap/basic.html

—. (2010f, March 8). *Ground-Level Ozone*. Retrieved August 7, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/air/ozonepollution/

—. (2010g, May 13). *Preferred/Recommended Models l TTN - Support Center for Regulatory Atmospheric Modeling*. Retrieved August 2, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/scram001/dispersion_prefrec.htm

—. (2010h). *Proposed Transport Rule Would Reduce Interstate Transport of Ozone and Fine Particle Pollution.* Retrieved July 18, 2010, from U.S. Environmental Protection Agency, Air and Radiation: http://www.epa.gov/airquality/transport/pdfs/FactsheetTR7-6-10.pdf

U.S. Government Accountability Office (U.S. GAO). (2003). *Freshwater Supply: States' Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Storage.* Retrieved September 4, 2010, from U.S. Government Accountability Office: http://www.gao.gov/products/GAO-03-514

United Nations Environment Programme (UNEP). (2001). *Vital Climate Graphics*. Retrieved July 26, 2010, from United Nations Environment Programme, Environmental Knowledge for Change: http://www.grida.no/publications/vg/climate/

U.S. Geological Survey (USGS). (1998). *Estimated Use of Water in the United States in 1995. Circular 1200.* Retrieved June 2, 2010, from U.S. Geological Survey: http://water.usgs.gov/watuse/pdf1995/html/

—. (2009). *Estimated Use of Water in the United States in 2005. Circular 1344.* Retrieved June 2, 2010, from U.S. Geological Survey: Water Use in the United States: http://water.usgs.gov/watuse/

—. (2010, April 1). *Water Science Glossary of Terms*. Retrieved September 5, 2010, from U.S. Geological Survey: http://ga.water.usgs.gov/edu/dictionary.html#W

Wei, M., Patadia, S., & Kammen, D. M. (2009, February). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry create in the US? *Energy Policy* , pp. 919-931.

Western Resource Advocates. (2008). *A Sustainable Path: Meeting Nevada's Water and Energy Demands.* Retrieved July 10, 2010, from Western Resource Advocates: http://www.westernresourceadvocates.org/water/NVenergy-waterreport.pdf

Western Resource Advocates. (2009). *A Sustainable Path: Meeting Future Water and Energy Demands in the Arkansas River Basin.* Retrieved July 10, 2010, from Western Resource Advocates: http://www.westernresourceadvocates.org/water/ArkansasBasinSustPathExecSum.pdf

Wisconsin Public Service Commission (WI PSC). (2009). *Electric Power Plants.* Retrieved September 8, 2010, from Public Service Commission of Wisconsin: http://psc.wi.gov/thelibrary/publications/electric/electric04.pdf

World Resources Institute (WRI). (2000). *The Environmentall Information Portal*. Retrieved November 7, 2010, from World Resources Institute, Earth Trends: http://earthtrends.wri.org/maps_spatial/maps_detail_static.php?map_select=196&theme=1

WRI. (2009). *Southeast Energy Opportunities: Water and Watts.* Retrieved July 10, 2010, from World Resources Institute, Southeast Energy Policy Briefs: http://www.wri.org/publication/southeast-energy-policy

Wuebbles, D. D. (2010, August 11). *The Role of Humanity in Climate Change: Scientific Understanding and Uncertainties*. Retrieved September 21, 2010, from University of Illinois Department of Atmospheric Sciences: http://www.ametsoc.org/boardpges/cwce/docs/profiles/WuebblesDonaldJ/2010-08-AMS-SCM-Slides.pdf

Appendix A. Metrics Considered for Analysis

Metric	Quantifiable?	Ease of Quantifying	Additional Notes
Environmental Impacts			
CO_2 emissions avoided	Yes	Low difficulty	Pay attention to what the solar project replaces (i.e., forested land, greenfield). Resources available: Stern Report, GHG protocol, EPA CO_2 calculator.
NO_X emissions avoided	Yes	Low difficulty	Analysis will also include avoided cost of emissions permits
Water conserved	Partially	Low difficulty	
Loss of wildlife habitat (greenfield remediation)	No	High difficulty	Of secondary importance to Axio, they are focusing on brownfields
Brownfield remediation	Partially	High difficult	Very relevant to Axio, but very difficult to generalize as benefits will depend on many site-specific factors.
Community Impacts			
Jobs created	Yes	Medium difficulty	Project specific; will depend on many site-specific factors. Resources available: Navigant Consulting, Vote Solar
Community impact of job creation	No	High difficulty	Project specific; will depend on many site-specific factors.
Displacement of agriculture	Partially	Medium difficulty	Unlikely to have material effect in near future because of cost of land and availability of other land
Public Health Impacts			
Reduction in local air pollution	Partially	Medium difficulty	
Health benefits of removing fertilizer from agricultural land	No	High difficulty	Unlikely to have material effect in near future because of cost of land and availability of other land
Health benefits of brownfield remediation	No	High difficulty	

Appendix B. Water Use in Electric Power Sector

Water resources play an important role in the power plant siting process, particularly in areas prone to drought. This appendix examines the water use factors of thermoelectric power cycles and of renewable energy technologies.

When describing and quantifying water use in the electric power sector, it is important to distinguish between water withdrawal and water consumption. The U.S. Geological Survey (USGS) defines a water withdrawal as water removed from a ground or surface water source for use. The water withdrawn is returned after it is used; however, the quality of the returned water may not be the same as when it was withdrawn initially (USGS 2009). USGS uses water consumption to refer to, "that part of water withdrawn that is evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment." (USGS 2010)

Figure B.1 below lists the typical withdrawal and consumption rates for fossil fuel, nuclear, and natural gas/oil combined cycle power plants for the cooling system types described above.[1] Approximately 43 percent of the thermoelectric power plants in the nation use a once-through cooling system; the majority of these power plants are in the eastern U.S. (NETL 2009). Recent EPA regulations, however, require most new power plants to use closed loop cooling system (USEPA 2001). Only 10 thermoelectric power plants built since 1980 use open loop cooling systems (USDOE 2006). Less than 1 percent of thermoelectric power plants use dry recirculating systems, 14.5 percent use recirculating systems with cooling ponds, and the remaining 42 percent use recirculating systems with cooling towers (NETL 2009).

It is important to note that the withdrawal and consumption rates presented in Figure B.1 are estimates. The exact amount of water required by a power plant will vary by location and will depend primarily on the average temperature and humidity at the plant site and the quality of water used at the plant (NREL 2002).

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[1] EPRI established representative, or typical, values or ranges of values for each cooling system type by reviewing EPRI reports, statistics published by regulatory agencies (e.g., Nuclear Regulatory Commission), statistics published by industry associations (e.g., Nuclear Energy Institute), and engineering handbooks. EPRI did not include boiler cycle makeup water and blowdown, ash sluice water, and other "service water" withdrawals and discharges in these estimates

Figure B.1 Water Withdrawal & Consumption Rates by Thermal Power Plant and Cooling System Type

Plant Type	Cooling System Type	Water Withdrawal (gal/MWh)	Water Consumption (gal/MWh)
Coal steam	Once-through cooling	22,600 – 27,000	120 – 140
	Recirculating	530 – 670	460 – 520
	Cooling pond	15,000 – 17,900	64 – 800
Nuclear steam	Once-through cooling	31,500	140
	Recirculating	1,100	620
Oil/gas steam	Once-through cooling	86,000	340
	Recirculating	950	600
	Cooling pond	29,900	420
Natural gas combined-cycle	Once-through cooling	9,010	20
	Recirculating	150	130
	Cooling pond	5,950	240
	Dry cooling	4	4

(NETL, Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements 2009)

Although carbon-capture technologies are not yet in service in power plants in the U.S., the National Energy Technology Laboratory (NETL) estimates that these technologies will increase the amount of water used at the plant considerably. Power plants with carbon capture technologies will use water to cool the gas that comes out of the combustion chamber (called flue gas) and to compress and dehydrate the CO_2 (NETL 2009). Figure B.2 below compares the estimated water requirements for power plants with carbon capture to those without.

Figure B.2 Estimated Water Withdrawal and Consumption for Fossil Plants with Carbon Capture

Power plant	Cooling type	Withdrawal (gal/MWh)	Consumption (gal/MWh)
Coal	Wet tower, subcritical	1480 (690)	1330 (680)
	Wet tower, supercritical	1290 (600)	1150 (590)
	Wet tower, retrofitted plant	9500	340
IGCC	Wet tower	580-660 (370-480)	480-530 (360-380)
NGCC	Wet tower	550 (260)	500 (260)

IGCC = integrated gasification combined cycle; NGCC = natural gas combined cycle

Assumes 90% capture efficiency, numbers in parentheses denote the values without carbon capture technology

(Fthenakis and Kim 2010)

Life Cycle Analysis

The impact of thermoelectric power on water resources extends beyond the water used at the power plant. The acquisition, preparation, transportation, and disposal of coal, natural gas, oil, and uranium as well as the construction of the plant and the manufacturing of equipment used at the plant also require water. Figure B.3 below shows the amount of water consumed and withdrawn in the preparation of fuel used at thermoelectric power plants in the U.S. In the figure, “upstream” water usage refers to the water withdrawals embedded in the materials and energy.

Figure B.3 Upstream Water Consumption and Withdrawal Rates for Thermoelectric Fuels

Fuel	Stage	Withdrawal (gal/MWh)	Withdrawal upstream (gal/MWh)	Consumption (gal/MWh)
Coal	Surface mining **	10	39	3-14
	Underground mining	50	134	8-53
	Washing	Not available	Not available	8-17
	Benefication	12	14	11-12
	Transportation - train	Not available	7-10	Not available
	Transportation – slurry pipeline	119	819	111-230
	Power plant construction	Not available	3-12	Not available
Nuclear	Surface uranium mining	10	4	53
	Underground uranium mining	10	4	1
	Milling	5	18	22-26
	Conversion	4	2	11
	Enrichment – diffusion	21	304	12-34
	Enrichment – centrifuge	2	27	1-5
	Fabrication	1	0.11	3
	Power plant construction	Not available	5-10	Not available
	Spent fuel disposal	Not available	5	Not available
Natural gas	Extraction – on shore	34	79	Negligible
	Extraction – off shore	0.21	0.11	Negligible
	Purification	17	Not available	15
	Pipeline transportation	0.40	10	8
	Underground storage	Not available	4	Not available
	Power plant environmental control	Not available	235	Not available

** Data for Eastern US only; data for western surface mining unknown

(Fthenakis and Kim 2010)

Before coal is combusted in the boiler of a power plant, it is mined, cleaned, and transported to the plant (Fthenakis and Kim 2010). Coal mining operations use water to wash coal, remove sulfur, suppress dust, and reclaim vegetation for the surface. The specific amount of water used depends on the technique used to extract the coal. Similarly, the life cycles for oil and natural gas require water for extraction, refinement, and transportation (Sovacool and Sovacool 2009).

For the nuclear process, uranium ore must be extracted and enriched before it is formed into pellets, stacked into fuel rods, and bundled into a nuclear reactor core. After extraction, uranium ore is milled (crushed and ground) to produce a concentrate known as “yellow cake”, which is then converted into uranium hexafluoride. The uranium hexafluoride must then be enriched to increase the concentration of uranium-235, the isotope used in nuclear fission. The mining and enrichment phases of the uranium fuel cycle are the most water intensive (Fthenakis and Kim 2010) (Sovacool and Sovacool 2009).

Figure B.4 lists the average[2] life-cycle water withdrawals for each thermoelectric fuel type in the U.S. in gallons per MWh and also in a more tangible measure of water volume, number of bathtubs per MWh.

Figure B.4 Average Life-Cycle Water Withdrawals in the U.S.

Thermoelectric fuel	Life-cycle withdrawals (gal/MWh)	Life-cycle withdrawals (No. of bathtubs[3]/MWh)
Coal	12,700	254
Nuclear	12,900	257
Oil/gas	14,850	297
Natural gas combined-cycle	1060	21

(Fthenakis and Kim 2010)

Oil/gas power plants withdraw more water on average than the other thermoelectric fuel plants. The natural gas combined-cycle power plant withdraws significantly less water than the other fuel types. For thermoelectric fuel cycles, on-site cooling during electricity generation is the most water intensive stage of the life cycle (Fthenakis and Kim 2010).

Water Quality

Thermoelectric power plants can affect the water quality of the lakes, rivers, and streams they use as a water source. Plants with once-through cooling systems return heated water to the water source. Water temperature deltas (i.e., large temperature differences between intake and discharge waters) can alter the chemical composition of the water source and increase the occurrence of eutrophication. Severe or prolonged instances of eutrophication can damage ecosystems, decrease the aesthetic and recreational value of the water body, and complicate drinking water treatment (Sovacool and Sovacool 2009).

Plant operators typically add chlorine to intake water to control microbes that can corrode pipes. Cooling water discharged from a thermoelectric power plant, regardless of the type of cooling system employed by the plant, contains trace amounts of chlorine and its by-products. Chlorine can be toxic to aquatic life, even at low concentrations; chlorine and biocide discharges are subject to state and federal water quality standards. In addition, high water temperatures can magnify the impacts of chlorine (Clean Air Task Force and the Land and Water Fund of the Rockies 2003).

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[2] The life-cycle water withdrawals depend on the type of cooling system each plant uses. Fthenakis and Kim calculated the average withdrawals per thermoelectric fuel type using data from NTEL. NTEL determined that the percentages of cooling type for the U.S. thermoelectric power plants are as follows: coal (48% recirculating, 39.1% once-through, 0.2% dry, 12.7% cooling pond), nuclear (43.6% recirculating, 38.1% once-through, 0% dry, 18.3% cooling pond), oil/gas (23.8% recirculating, 59.2% once-through, 0% dry, 17.1% cooling pond), and combined cycle (30.8% recirculating, 8.6% once-through, 59% dry, 1.7% cooling pond).

[3] Assume that one bathtub holds 50 gallons of water.

Water that is reused in a close loop cooling system requires more chemical treatment to eliminate solids and salts that accumulate as the water evaporates. Water returned to its source after blowdown in plants with a closed loop cooling system that uses a cooling tower thus contains more dissolved and suspended solids than water used in once-through cooling systems (Sovacool and Sovacool 2009).

Boiler blowdown (water purged periodically from the boiler) and cleaning wastes from thermoelectric plants can contain trace amounts of copper, iron, nickel, zinc, chromium, and magnesium and are sent to a wastewater treatment facility. Additional sources of water discharge at the power plant site include: coal pile runoff, water used for coal cleaning, and water used to dilute waste from air emissions control devices (Clean Air Task Force and the Land and Water Fund of the Rockies 2003).

Coal and uranium mining and oil shale development can also affect water quality. Runoff from mine operations and from piles of waste rock that accumulate at the process plant (called a tailings pile) can reduce the pH and increase the concentrations of heavy metals in the mine drainage water. Fuel additives, such as methyl tertiary-butyl ether (MTBE), have the potential to contaminate groundwater (USDOE 2006).

Photovoltaics

The operation of photovoltaic (PV) technologies requires water, which is used to clean and cool the wafers, cells, and modules. Looking at the entire life cycle of a PV panel, the production and processing of raw materials (upstream processes) and the manufacturing process used to make the panel require water.

Figure B.5 Water Withdrawals and Consumption for PV Technologies

	Manufacturing withdrawals (gal/MWh)	Upstream withdrawals (gal/MWh)	On-site withdrawals during operation (gal/MWh)	On-site consumption during operation (gal/MWh)	Notes
Frame	53	388	N/A	N/A	Based on multi-Si PV
Balance of system (BOS)	51	404	N/A	N/A	Based on ground-mount multi-Si PV
Multi-Si panel	Not available	17	N/A	N/A	Efficiency = 13.2%
Mono-Si panel	0.21	152	N/A	N/A	Efficiency = 14%
CdTe panel	0.40	55	N/A	N/A	Efficiency = 10.9%
Cleaning			4	4	

Assumptions: insolation 1800 kWh/m^2/year, lifetime of 30 years, performance ratio of 0.8

(Fthenakis and Kim 2010)

Figure B.5 above compares the water withdrawals and consumption needed to manufacture and operate three common PV technologies: multi-crystalline silicon (multi-Si), mono-crystalline silicon (mono-Si), and thin film cadmium telluride (CdTe). Silicon-based PV panels require more PV material than cadmium telluride panels and thus need more water to produce (Fthenakis and Kim 2010).

Concentrated Solar Power

Concentrated solar power systems (CSP) use lenses or mirrors to focus sunlight on a small area. The systems direct this concentrated light onto photovoltaic surfaces or onto a receiver tube of heat transfer fluid to generate electricity.

Parabolic trough technologies employ parallel rows of solar collectors, each with a parabolic-shaped reflector. These reflectors focus sunlight onto a linear receiver than contains heat transfer fluid (HTF). The HTF flows from the panels in the solar field to a solar superheater. The superheat generates steam, which is used to power a turbine-generator to produce electricity. The HTF then passes through a condenser before returning to the solar field (NREL 2003). The condenser usually requires cooling water; however, there are some trough technologies that employ dry cooling systems. Dry cooling systems do not require as much water, but are more expensive and do not perform as well as wet cooling systems (NREL 2006).

A solar power tower uses heliostats (mirrors that track the sun) to reflect sunlight onto a central receiver on top of a tower. The receiver contains salt water or sodium. When heated, the salt water/sodium produces steam for a conventional turbine/generator system; the system requires cooling water. Sodium has a high heat capacity and can store energy, allowing the tower to generate power in the absence of sunlight (NREL 2003).

A dish Stirling system uses a large parabolic dish that focuses sunlight to a single point above the dish where a receiver captures heat. The dish is connected to a Stirling engine that directly converts the concentrated heat to electricity without the use of cooling water (Fthenakis and Kim 2010).

Concentrating photovoltaic (CPV) systems use parabolic PV panels to concentrate sunlight onto a small semiconductor cell. CPV systems do not use cooling water (NREL 2006). Figure B.6 below compares water withdrawals and consumption for the operation of concentrated solar power systems.

Figure B.6 Water Withdrawal and Consumption for Concentrated Solar Power Systems

Type		Withdrawal (gal/MWh)	Consumption (gal/MWh)	Condition
Concentrating solar power	Tower	770	770	
	Tower	850	850	2700 kWh/m2/year (DNI)
	Tower, wet cooling	820	820	SEGS 6/7
	Parabolic trough, wet cooling	980	980	250 W/m2 (DNI), hypothetical
	Parabolic trough, dry cooling	80	80	250 W/m2 (DNI), hypothetical
	Parabolic trough, wet cooling	820	820	SEGS 6/7
	Parabolic trough, wet cooling	820-1000	820-1000	SEGS 3-7, 1995, actual
	Trough	550	550	2891 kWh/m2/year (DNI)
	Dish Stirling	4	4	Cleaning
Concentrated photovoltaic		4	4	Cleaning

(Fthenakis and Kim 2010)

In general, CSP systems use more water than conventional power plants because the steam cycle is less efficient (partially due to the need to pump the HTF) (Fthenakis and Kim 2010). All CSP systems require a small amount of water to wash the solar field (NREL 2006).

Geothermal

Geothermal power plants use heat stored in the earth to generate electricity. Dry-steam geothermal systems pump steam from underground directly into a steam turbine. A hot water geothermal system extracts hot, pressurized liquid (or a mix of liquid and vapor) from underground. As pressure drops, the hot water releases steam, which is sent to a steam turbine. Geothermal plants use a cooling tower to discharge waste heat and thus need fresh water for blowdown. Some plants use steam condensate for cooling and do not need to withdraw additional water (Fthenakis and Kim 2010).

Figure B.7 below compares water withdrawals and consumption for dry and hot water geothermal systems. Geothermal power plants use more water than steam fossil fuel plants because the steam cycle is less efficient (Fthenakis and Kim 2010). Drilling operations for geothermal wells also use a small amount of fresh water to cool the drill bit and to remove rock chips, but this is not included in the figures in the table below (DiPippo 2008).

Figure B.7 Water Withdrawal and Consumption for Geothermal Power Systems

Type		Withdrawal (gal/MWh)	Consumption (gal/MWh)
Geothermal	Dry system	2000	1400
	Dry system	1800	1800
	Hot water system	3960	400
	Hot water system	11,810	600-1800

(Fthenakis and Kim 2010)

Geothermal wells are surrounded by multiple cement casings in order to prevent subsurface leakage. Geofluids may contain minerals or elements (e.g., boron, arsenic) that could contaminate surface or groundwater sources and/or harm vegetation and animals (DiPippo 2008).

Wind

The operation of a wind turbine requires a small amount of water for cleaning. Looking at the entire life cycle of the wind turbine, the production and processing of raw materials (primarily steel, iron, and glass fiber) and the manufacturing process used to make the turbine require water (Fthenakis and Kim 2010).

Figure B.8 Water Withdrawals and Consumption for Wind Turbines

	Upstream withdrawal (gal/MWh)	On-site withdrawals during operation (gal/MWh)	On-site consumption during operation (gal/MWh)	Capacity factor
Off shore, Denmark	61	1	1	0.29
Off shore, Denmark	45	1	1	0.25
On shore, Denmark	85	1	1	0.46
On shore, Spain	55	1	1	0.32
On land, Denmark	45	1	1	0.19
On land, Italy	66	1	1	0.23

(Fthenakis and Kim 2010)

Figure B.8 above compares the water withdrawals and consumption needed for the upstream processes (materials production) and the operation of wind turbines in three countries. (Water withdrawals associated with turbine manufacturing are not available.) Offshore wind turbines require additional materials, but also generate more electricity than onshore turbines (Fthenakis and Kim 2010).

Hydroelectric

The use of river water at a hydroelectric power plant is not considered consumptive because it is immediately available to other users when it flows out of the dam and into the river. The reservoir created by the dam increases the surface area of the river, resulting in additional water evaporation from the surface, when compared to a free flowing river. The amount of water evaporated at a hydroelectric power plant is difficult to measure, as the climate, insolation, and the amount of shade (all of which affect the evaporation rate) varies widely among reservoirs (NREL 2003). According to one source U.S. average is 4,490 gallons per MWh, but this figure is based on a few estimates with a large variance (Fthenakis and Kim 2010).

The reservoir and the dam created for most hydroelectric power plants in the U.S. transforms the ecosystem and the flow regime of the source river. In order to impound a reservoir, engineers must flood the surrounding terrestrial, aquatic, and wetland habitats. This impoundment affects both the quality of the water and the wildlife populations that depend on the river. Suspended particles carried in the river can accumulate in a reservoir behind a dam and increase algal growth. The dam also disrupts flow regimes, prevents the transport of sediment and nutrients, and slows or inhibits the movement of aquatic species downstream. In many cases these changes have led to the irreversible loss of aquatic and terrestrial species populations and ecosystems (Dams 2002).

Biomass

Biomass, recently grown plant material that is used to produce energy, can come from a variety of sources: herbaceous and woody energy crops, agricultural food and feed crops, aquatic plants, wood waste and residues, agricultural crop residues, and other waste materials. The production of biomass for electricity generation requires water in two key phases: feedstock production and electricity generation.

The amount of water used to produce or grow biomass feedstocks depends on the type of feedstock, climate, precipitation patterns, farming and/or harvesting practices, and groundwater availability and varies substantially among feedstocks. The water demand for dedicated energy crops is the sum of water added to the crops through irrigation and the water lost from evapotranspiration.

Evapotranspiration losses include the loss of water from the soil through evaporation and the loss of water from the plant through transpiration. Water requirements for dedicated energy crops depend on the crop species, climate, irrigation type and efficiency, precipitation, and other agricultural conditions. Upstream water withdrawals required for energy crop production include the water embedded in fertilizers, pesticides, and herbicides and the fuel and electricity required for cultivation, irrigation, and harvesting (Fthenakis and Kim 2010).

It is also difficult to quantify water use associated with waste and residue feedstocks. Certain analyses consider residues or wastes from forestry or agriculture to be secondary products, and do not include the water used to grow or irrigate the primary crops (Dennen, et al. 2007).

All biomass energy generation processes require water during the combustion stage of the fuel cycle, regardless of the primary feedstock used at the plant. The processes used to convert biomass feedstocks into energy used to produce electricity can be grouped into three categories:

- **Direction combustion**: burn soil biomass feedstock in a boiler to produce hot water and use a steam generator to generate electricity.
- **Co-firing**: substitute solid biomass feedstock for a portion of the fossil fuel (typically coal) used in the combustion process at the plant.
- **Gasification**: convert solid biomass feedstock to syn gas (synthesis gas, composed primarily of carbon monoxide, carbon dioxide, and hydrogen) by heating the biomass to very high temperatures inside a gasifier with limited oxygen. Syn gas can be burned in a combustion engine or used in a gas turbine. (USEPA and NREL 2009)

In their water use analyses, EPRI assumes that the steam conditions (and therefore the cooling water withdrawal and consumption rates) for a power plant burning biomass is comparable to those for a plant burning fossil fuels (EPRI 2002). Fthenakis and Kim, however, list biomass separately from fossil fuel plants (Fthenakis and Kim 2010). The results of both studies are presented in Figure B.9 below.

Figure B.9 Water Withdrawal and Consumption at Biomass Power Plant

Plant Type	Cooling System Type	Water Withdrawal (gal/MWh)	Water Consumption (gal/MWh)	Source
Biomass fueled steam	Once-through cooling	20,000 – 50,000	~ 300	EPRI
	Pond cooling	300 – 600	300 – 480	EPRI
	Cooling towers	500 – 600	~ 480	EPRI
	Steam plant	480	480	Fthenakis & Kim
Bio-gas steam	Wet cooling	550	450	Fthenakis & Kim
	Dry cooling	40	0	Fthenakis & Kim

The conversion of undeveloped land to agricultural uses to produce biomass feedstocks can affect water quality and increase nutrient runoff into surrounding water bodies, especially if the crops planted require fertilizer and/or pesticide inputs (USEPA and NREL 2009).

Summary

Figure B.10 below summarizes the water use withdrawal and consumption data (for electricity generation only) for renewable fuel cycles presented in the above sections.

Figure B.10 Water Withdrawals and Consumption – Thermoelectric and Renewable Power[4]

		ELECTRICITY GENERATION ONLY		TOTAL LIFE CYCLE	
		Water Withdrawal (gal/MWh)	Water Consumption (gal/MWh)	Water Withdrawal (gal/MWh)	Water Withdrawal (No.bathtubs[5]/MWh)
Solar PV	Multi-Si	4	4	530	11
	CdTe	4	4	210	4
Wind	Denmark	1	1	60	1.5
Hydro	U.S. average	0	4490	20	0.5
Biomass	Southwest (irrigation)			115,720	2300
	Midwest (no irrigation)			530	11

(Fthenakis and Kim 2010) (EPRI 2002)

The biomass plant located in the southwestern U.S. and the hydropower plant withdraw the most and least water, respectively, over the entire life cycle. (Fthenakis and Kim did not have sufficient upstream data to compare water consumption over the entire life cycle.) With the exception of biomass produced using irrigation, most water used for renewable electricity generation is used upstream (embodied in materials) and in production of the equipment (Fthenakis and Kim 2010).

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[4] To illustrate two contrasting cases for biomass: one requires irrigation in the arid Southwestern US, and the other, in Midwestern US, does not. A comprehensive, representative figure for the biomass-to-electricity scheme is unavailable due to lack of large-scale biomass-based power plants together with variable farming conditions (e.g., precipitation, nutrient, and soil conditions) in different agricultural areas. The PV fuel cycle withdraw estimates were calculated using the US average insolation of 1800 kWh/m^2/year. Fthenakis and Kim note that the lifecycle inventory data they reviewed for the wind cycle generally are less detailed than those for the PV cycle, warranting more detailed investigation of the former.

[5] Assume that one bathtub holds 50 gallons of water.

References

Clean Air Task Force and the Land and Water Fund of the Rockies. *The Last Straw: Water Use by Power Plants in the Arid West.* Hewlett Foundation Energy Series, 2003.

Dams, World Commission on. "Chapter 3: Ecosystems and Large Dams: Environmental Performance." In *Dams and Development: A New Framework for Decision-Making*, by World Commission on Dams, 73-95. London: Earthscan Publications Ltd, 2002.

Dennen, B., D. Larson, C. Lee, J. Lee, and S. Tellinghuisen. *California's Energy-Water Nexus: Water Use in Electricity Generation.* Master's Project, Donald Bren School of Environmental Science & Management, University of California, Santa Barbara, 2007.

DiPippo, R. "Chapter 19: Environmental Impact of Geothermal Power Plants." In *Geothermal Power Plants: Principles, Applications, Case Studies, and Environmental Impact*, by R. DiPippo, 385-410. Oxford: Butterworth-Heinemann, 2008.

Electric Power Research Institute (EPRI). *Water & Sustainability (Volume 3): U.S. Water Consumption for Power Production - The Next Half Century.* 1006786, Palo Alto, CA: Electric Power Research Institute, 2002.

Fthenakis, V., and H.C. Kim. "Life-cycle uses of water in U.S. electricity generation." *Renewable and Sustainable Energy Reviews* 14 (2010): 2039-2048.

National Energy Technology Laboratory (NETL). *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements.* National Energy Technology Laboratory, 2009.

National Renewable Energy Laboratory (NREL). *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts.* NREL/SR-550-34440, Golden, CO: National Renewable Energy Laboratory, 2003.

—. *Consumptive Water Use for U.S. Power Production.* NREL/TP-550-39905, Golden, CA: National Renewable Energy Laboratory, 2003.

—. *Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California.* NREL/SR-550-39291, Golden, CO: National Renewable Energy Laboratory, 2006.

Sovacool, B.K., and K.E. Sovacool. "Preventing National Electricity-Water Crisis Areas in the United States." *Columbia Journal of Environmental Law* 34 (2009): 333-393.

USDOE. "Energy Demands on Water Resources." 2006.

U.S. Environmental Protection Agency and National Renewable Energy Laboratory (USEPA and NREL). *State Bioenergy Primer.* EPA 430-R-09-024; NREL /TP-6A2-44688, Washington, D.C.:

USEPA. "National Pollutant Discharge Elimination System: Regulations Addressing Cooling Water Intake Structures for New Facilities; Final Rule." *Federal Register, 40 CFR Parts 9, 122, et al.* December 18, 2001.

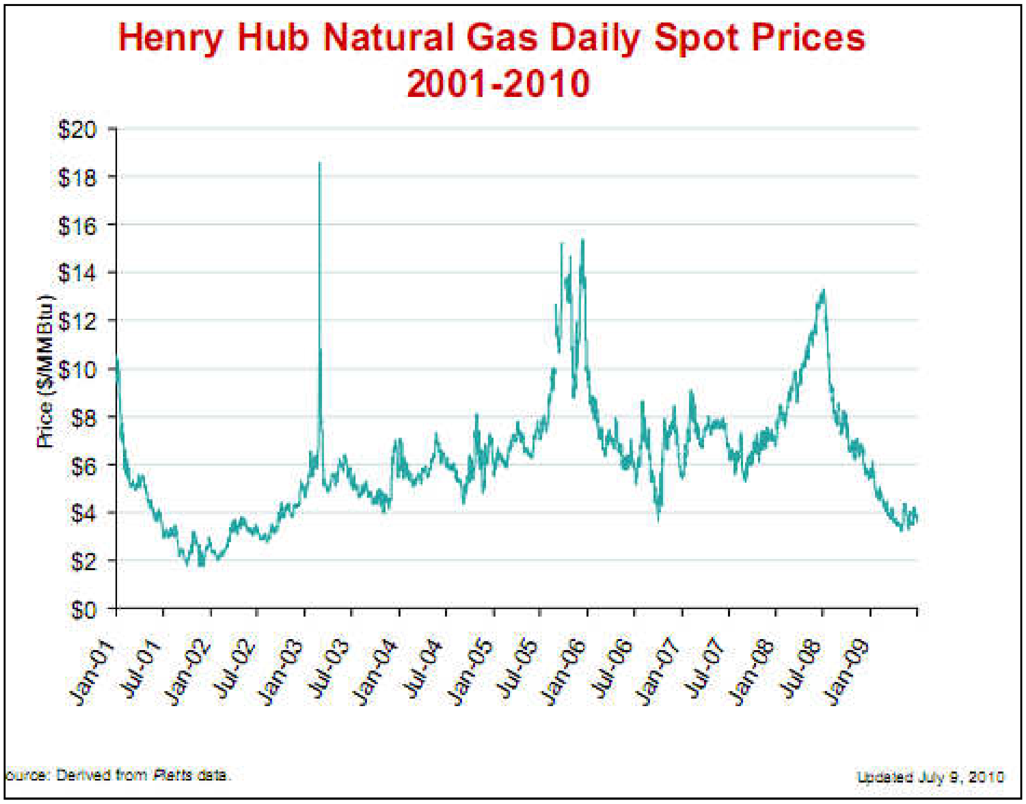
U.S. Geological Survey (USGS). *Estimated Use of Water in the United States in 2005.* Reston: U.S. Geological Survey, 2009.

—. *Water Science Glossary of Terms.* April 1, 2010. http://ga.water.usgs.gov/edu/dictionary.html#W (accessed September 5, 2010).

Appendix C: Natural Gas

In order to make comparisons of costs of PV to natural gas, baselines are generally helpful; natural gas is generally used as a major component of these baseline projections. There is precedent in California – the nation’s largest state in terms of energy consumption and location of the country’s most aggressive renewable portfolio standard (RPS) – of a similar baseline projection. The California Public Utilities Commission (CPUC) sets a production-based incentive annually, known as the Market Price Referent (MPR). The MPR reflects the New York Mercantile Exchange (NYMEX) forward pricing data on natural gas in addition to the upfront capital costs of constructing a new gas turbine generating facility (California Public Utilities Commission (CPUC) 2009). The CPUC calculates the estimated range of costs associated with various greenhouse gas (GHG) compliance scenarios using Synapse’s annual CO_2 price forecasting report. We have taken this into account – along with other price forecasts – in our discussion below regarding emissions compliance costs.

Figure C-1 Natural Gas Spot Prices, 2001-2010



(FERC 2010)

Forecasting natural gas production and supply as well as price, has traditionally been a challenging task – particularly in the last ten years. Price volatility further exacerbated this problem making cost-benefit analyses of switching generation to natural gas generation difficult to estimate. Figure A-1 above highlights some of the recent fluctuations in the price of Henry Hub natural gas daily spot prices from 2000 to 2010. Our analysis assumes that future uncertainty regarding natural gas prices or the supply of natural gas will not slow the general growth in natural gas generation. It is important to note that past supply concerns regarding natural gas in the U.S. resulted in dramatic changes in our new generation capacity decision making process. Most notably in 1977 when rumors of a supply shortage prompted Congress to pass the Power Plant and Industrial Fuel Use Act (FUA) which prevented the construction of all new gas-fired power plants. FUA was in place from 1977-1987 during which the U.S. added 172 gigawatts (GW) of new generation capacity – 81 GW was new coal capacity, equivalent to 26% of today's entire coal fleet (MIT 2010). The remaining capacity was largely met through nuclear power (MIT 2010). Since 1987 the U.S. has added 361 GW of generation capacity – 70% is gas fired and 11% coal fired; however, the nameplate capacity of our natural gas power plant fleet is largely underutilized (MIT 2010). This would likely change under an emissions trading scheme as gas-fired power would replace power generated from older, dirtier coal-fired plants.

<u>References:</u>

FERC. *FERC: Natural Gas Markets National Overview.* July 2010. http://www.ferc.gov/market-oversight/mkt-gas/overview.asp (accessed July 22, 2010).

MIT. *The Future of Natural Gas: An Interdisciplinary MIT Study (Interim Report).* Massachusetts Institute of Technology, 2010.

Appendix D. NO_X Limiting Technologies

Figure D-1 External Combustion NO_X Limiting Technologies

Technique	Description	Advantages	Disadvantages	Impacts	Applicability
Less Excess Air (LEA)	Reduces oxygen availability	Easy modifications	Low NO_X reduction	High CO Flame length Flame stability	All fuels
Off Stoichiometric a. Burners Out of Service (BOOS) b. Over Fire Air (OFA)	Staged combustion	Low cost No capital cost for BOOS	a. Higher air flow for CO b. High capital cost	Flame length Fan capacity Header pressure	All fuels Multiple burners for BOOS
Low NO_X	Internal staged combustion	Low operating cost Compatible FCR	Moderately high capital cost	Flame length Fan capacity Turndown stability	All fuels
Flue Gas Recirculation (FGR)	<30% flue gas recirculated with air, decreasing temperature	High NO_X reduction Potential for low nitrogen fuels	Moderately high capital cost and operating cost Affects heat transfer and system pressures	Fan capacity Furnace pressure Burner pressure drop Turndown stability	All fuels Low nitrogen fuels
Water Steam Injection	Reduces flame temperature	Moderate capital cost NO_X reduction similar to FGC	Efficiency penalty Fan power higher	Flame stability Efficiency penalty	All fuels as Low nitrogen fuels
Reduced Air Preheat	Air not preheated, reduces flame temperature	High NO_X reduction potential	Significant efficiency loss (1% per 40°F)	Fan capacity Efficiency penalty	All fuels Low nitrogen fuels
Selective Catalytic reduction (SCR) (add-on technology)	Catalyst located in the air flow, promotes reaction between ammonia and NO_X	High NO_X removal	Very high capital cost High operating cost Catalyst siting Increased pressure drop Possible water wash required	Space requirements Ammonia slip Hazardous waste Disposal	All fuels
Selective Non-Catalytic Reduction (SNCR) (add-on technology) a. urea b. ammonia	Inject reagent to react with NO_X	a. Low capital cost Moderate NO_X removal Non-toxic chemical b. Low operating cost	a. Temperature dependent NO_X reduction less at lower loads b. Moderately high	a. Furnace geometry Temperature profile b. Furnace geometry	All fuels

Technique	Description	Advantages	Disadvantages	Impacts	Applicability
		Moderate NO_X removal	capital cost Ammonia storage, handling, injection system	Temperature profile	
Fuel Reburning	Inject fuel to react with NO_X	Moderate cost Moderate NO_X removal	Extends residence time	Furnace temperature profile	All fuels (pulverized solid)
Combustion Optimization	Change efficiency of primary combustion	Minimal cost	Extends residence time	Furnace temperature profile	Gas Liquid fuels
Catalytic Combustion	Catalyst causes combustion to be at a low temperature	Lowest possible NO_X	Very high capital cost High operating cost Catalyst siting	Space requirements Disposal	Gas Liquid fuels
Non-Thermal Plasma	Reducing agent ionized or oxidant created in flow	Moderate cost Easy siting High NO_X removal	Fouling possible Ozone emission possible	Uses electrical power	All fuels
Inject Oxidant	Chemical oxidant injected in flow	Moderate cost	Nitric acid removal	Add-on	All fuels
Oxygen instead of Air	Uses oxygen to oxidize fuel	Moderate to high cost Intense combustion	Eliminates prompt NO_X Furnace alteration	Equipment to handle oxygen	All fuels
Ultra-Low Nitrogen Fuels	Uses low-nitrogen fuel	Eliminates fuel NO_X No capital cost	Slight rise in operating cost	Minimal charge	All ultra-low nitrogen fuels
Use Sorbents (add-on technology) in: a. Combustion b. Duet to Baghouse c. Duet to Electrostatic Precipitator	Use a chemical to absorb NO_X or an adsorber to hold it	Can control other pollutants as well as NO_X Moderate operating cost	Cost of handling sorbent Space for the sorbent storage and handling	Add-on	All fuels
Air Staging	Admit air in separated stages	Reduce peak combustion temperature	Extend combustion to a longer residence time at lower temperature	Adds duets and dampers to control air Furnace modification	All fuels
Fuel Staging	Admit fuel in separated stages	Reduce peak combustion temperature	Extend combustion to a longer residence time at lower temperature	Adds fuel injectors to other locations Furnace modification	All fuels

Source: Environmental Protection Agency – Office of Air Quality. *Nitrogen Oxides (NOx), Why and How They are Controlled.* Technical Bulletin, Research Triangle Park, NC: Environmental Protection Agency, 1999.

Appendix E. Costs of NOX Controls

Figure E-1 1997 Costs of NO_X Controls
Analyzing Electric Power Generation under the CAAA – Cost Estimates

Boiler Type	Control Type	Capital Cost ($/kW)	Fixed O&M ($/kW/yr)	Variable O&M (mils/kWh)	% Control
Wall Fired	LNB w/o OFA	16.8	0.25	0.05	67.5
Wall Fired	LNB w/ OFA	22.8	0.35	0.07	67.5
Tang-Fired	LNB w/ OFA	32.3	0.49	0	47.3
Tang-Fired	LNB w/ SOFA	34.7	0.53	0	52.3
Tang-Fired	LNB w/ BOFA	46.7	0.71	0.02	57.3
Cell Burners	Non Plug-In Comb. Ctl.	22.8	0.34	0.07	60
Cyclone	Coal Reburning	70.7	1.07	0.25	50
Wet Bottom	NO_X Comb. Ctl.	9.6	0.14	0.05	50
Vert. Fired	NO_X Comb. Ctl.	10.8	0.17	0.05	40
	SCR – Low NO_X Rate	69.7	6.12	0.24	70
	SCR – High NO_X Rate	71.8	6.38	0.4	80
	SNCR – Low NO_X Rate	16.6	0.24	0.82	40
	SNCR – Cyclone	9.6	0.14	1.27	35
	SNCR – High NO_X Rate	19	0.29	0.88	35
	Nat. Gas Reburn-Low	32.4	0.49		40
	Nat. Gas Reburn-High	32.4	0.49		50

Source: Environmental Protection Agency – Office of Air Quality. *Nitrogen Oxides (NOx), Why and How They are Controlled.* Technical Bulletin, Research Triangle Park, NC: Environmental Protection Agency, 1999.

Appendix F. The Value of a Statistical Life

The value used to quantify the value of a statistical life (VSL) can dramatically shift an analysis of the health benefits of a policy or avoided emissions. It is important to note that the VSL is not a quantitative value that an entity places on a human life, but rather a statistical amount derived from data regarding willingness to pay for small reduced risks of mortality. The EPA determines its VSL by aggregating data on consumers' willingness to pay for a reduced probability of mortality. For example, if the target consumers are willing to pay $500 each for a reduction in mortality risk of 1/10,000, the VSL value is $500 times 10,000, or $5 million (U.S. EPA 2000).

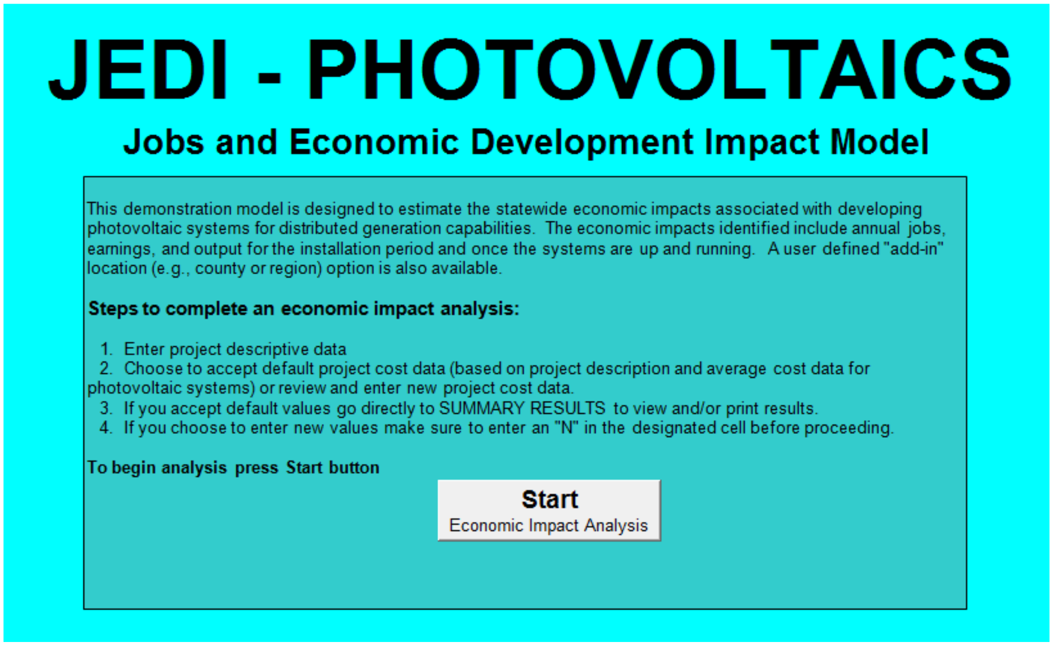
For EPA to arrive at its VSL of $6.9 million, it aggregated the results of about 25 studies that estimate VSL in different contexts. These studies estimated VSL in a range of $0.7 million to $16.3 million in 1997 U.S. dollars and warns that various demographic and risk factors will influence the VSL. Willingness to pay for incremental risk reduction varies greatly with age, for example; younger individuals may be willing to pay more than elderly individuals to reduce the concentration of an air pollutant like PM that has a cumulative health impact over decades. The current health status of an individual or population will also influence willingness to pay to reduce health risks. Additionally, the income available to consumers influences their willingness to pay, and those with low income have a stricter budget constraint than moderate- and high-income consumers. Individuals also place different values on different types of risks, considering whether the risk is ordinary or catastrophic, delayed or immediate, natural or man-made, controllable or uncontrollable, and necessary or unnecessary (U.S. EPA 2000). The time it takes a health effect to manifest after the risk is incurred and the effect a risk has on other people also influences the value an individual places on reducing a risk factor.

References:

U.S. EPA. *Guidelines for Preparing Economic Analyses.* Handbook, U.S. Environmental Protection Agency, Washington, D.C.: U.S. EPA, 2000.

Appendix G. JEDI Model Inputs and Results

Figure G.1 JEDI Model Introductory Page



JEDI - PHOTOVOLTAICS

Jobs and Economic Development Impact Model

This demonstration model is designed to estimate the statewide economic impacts associated with developing photovoltaic systems for distributed generation capabilities. The economic impacts identified include annual jobs, earnings, and output for the installation period and once the systems are up and running. A user defined "add-in" location (e.g., county or region) option is also available.

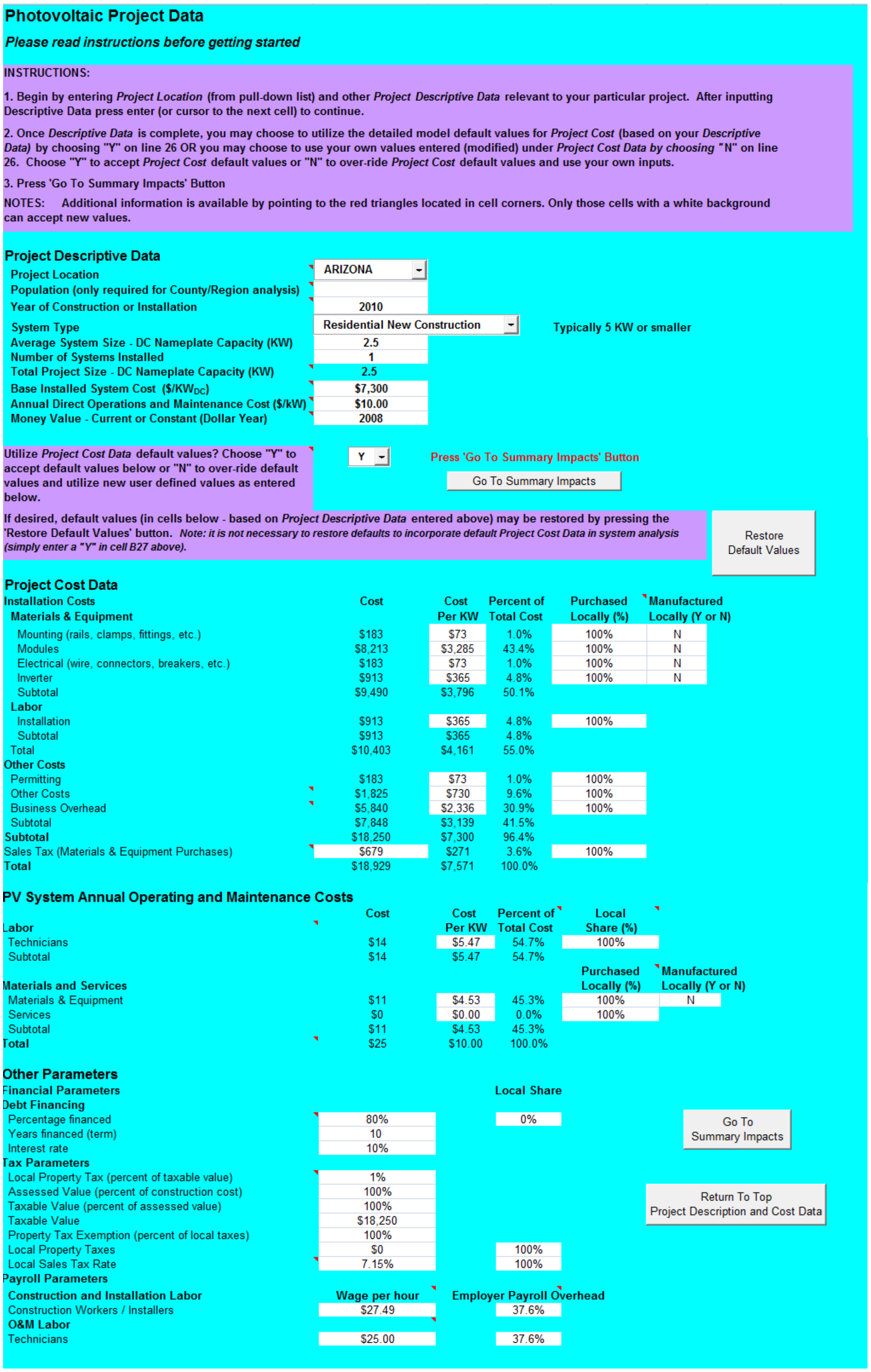
Steps to complete an economic impact analysis:

1. Enter project descriptive data
2. Choose to accept default project cost data (based on project description and average cost data for photovoltaic systems) or review and enter new project cost data.
3. If you accept default values go directly to SUMMARY RESULTS to view and/or print results.
4. If you choose to enter new values make sure to enter an "N" in the designated cell before proceeding.

To begin analysis press Start button

To access JEDI model see: http://www.nrel.gov/analysis/jedi/about_jedi.html

Figure G.2 JEDI Model Project Data Input Page



Photovoltaic Project Data

Please read instructions before getting started

INSTRUCTIONS:

1. Begin by entering *Project Location* (from pull-down list) and other *Project Descriptive Data* relevant to your particular project. After inputting Descriptive Data press enter (or cursor to the next cell) to continue.

2. Once *Descriptive Data* is complete, you may choose to utilize the detailed model default values for *Project Cost* (based on your *Descriptive Data)* by choosing "Y" on line 26 OR you may choose to use your own values entered (modified) under *Project Cost Data by choosing* "N" on line 26. Choose "Y" to accept *Project Cost* default values or "N" to over-ride *Project Cost* default values and use your own inputs.

3. Press 'Go To Summary Impacts' Button

NOTES: Additional information is available by pointing to the red triangles located in cell corners. Only those cells with a white background can accept new values.

Project Descriptive Data

Project Location	ARIZONA	
Population (only required for County/Region analysis)		
Year of Construction or Installation	2010	
System Type	Residential New Construction	Typically 5 KW or smaller
Average System Size - DC Nameplate Capacity (KW)	2.5	
Number of Systems Installed	1	
Total Project Size - DC Nameplate Capacity (KW)	2.5	
Base Installed System Cost ($/KW$_{DC}$)	$7,300	
Annual Direct Operations and Maintenance Cost ($/kW)	$10.00	
Money Value - Current or Constant (Dollar Year)	2008	

Utilize *Project Cost Data* default values? Choose "Y" to accept default values below or "N" to over-ride default values and utilize new user defined values as entered below. Y

Press 'Go To Summary Impacts' Button

If desired, default values (in cells below - based on *Project Descriptive Data* entered above) may be restored by pressing the 'Restore Default Values' button. ***Note: it is not necessary to restore defaults to incorporate default Project Cost Data in system analysis (simply enter a "Y" in cell B27 above).***

Project Cost Data

Installation Costs	**Cost**	**Cost Per KW**	**Percent of Total Cost**	**Purchased Locally (%)**	**Manufactured Locally (Y or N)**
Materials & Equipment					
Mounting (rails, clamps, fittings, etc.)	$183	$73	1.0%	100%	N
Modules	$8,213	$3,285	43.4%	100%	N
Electrical (wire, connectors, breakers, etc.)	$183	$73	1.0%	100%	N
Inverter	$913	$365	4.8%	100%	N
Subtotal	$9,490	$3,796	50.1%		
Labor					
Installation	$913	$365	4.8%	100%	
Subtotal	$913	$365	4.8%		
Total	$10,403	$4,161	55.0%		
Other Costs					
Permitting	$183	$73	1.0%	100%	
Other Costs	$1,825	$730	9.6%	100%	
Business Overhead	$5,840	$2,336	30.9%	100%	
Subtotal	$7,848	$3,139	41.5%		
Subtotal	$18,250	$7,300	96.4%		
Sales Tax (Materials & Equipment Purchases)	$679	$271	3.6%	100%	
Total	$18,929	$7,571	100.0%		

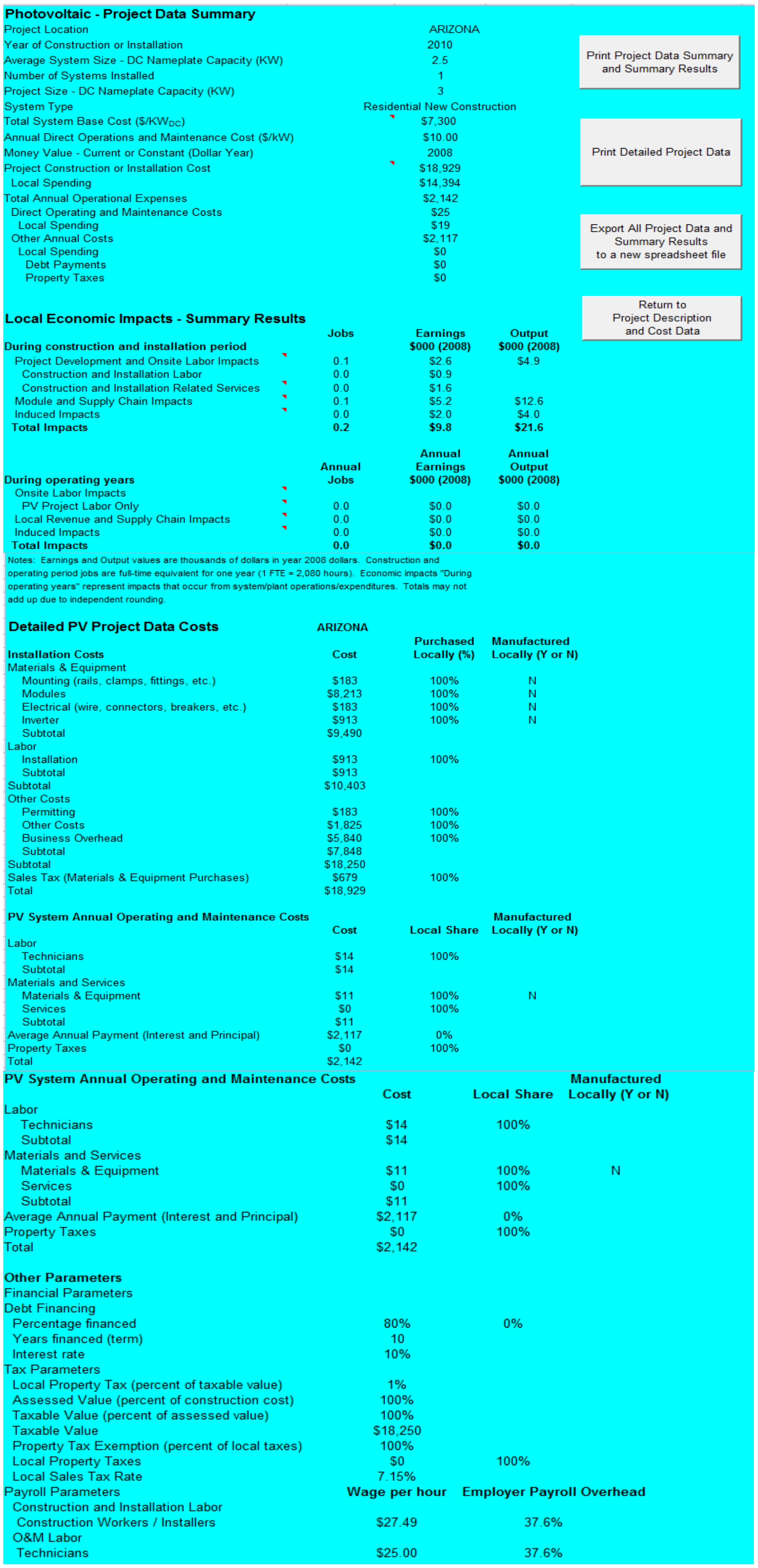
PV System Annual Operating and Maintenance Costs

	Cost	**Cost Per KW**	**Percent of Total Cost**	**Local Share (%)**	
Labor					
Technicians	$14	$5.47	54.7%	100%	
Subtotal	$14	$5.47	54.7%		
				Purchased Locally (%)	**Manufactured Locally (Y or N)**
Materials and Services					
Materials & Equipment	$11	$4.53	45.3%	100%	N
Services	$0	$0.00	0.0%	100%	
Subtotal	$11	$4.53	45.3%		
Total	$25	$10.00	100.0%		

Other Parameters

Financial Parameters		**Local Share**
Debt Financing		
Percentage financed	80%	0%
Years financed (term)	10	
Interest rate	10%	
Tax Parameters		
Local Property Tax (percent of taxable value)	1%	
Assessed Value (percent of construction cost)	100%	
Taxable Value (percent of assessed value)	100%	
Taxable Value	$18,250	
Property Tax Exemption (percent of local taxes)	100%	
Local Property Taxes	$0	100%
Local Sales Tax Rate	7.15%	100%
Payroll Parameters		
Construction and Installation Labor	**Wage per hour**	**Employer Payroll Overhead**
Construction Workers / Installers	$27.49	37.6%
O&M Labor		
Technicians	$25.00	37.6%

Figure G.3 Example of JEDI Model Results Page



Photovoltaic - Project Data Summary

Project Location	ARIZONA
Year of Construction or Installation	2010
Average System Size - DC Nameplate Capacity (KW)	2.5
Number of Systems Installed	1
Project Size - DC Nameplate Capacity (KW)	3
System Type	Residential New Construction
Total System Base Cost ($/KW$_{DC}$)	$7,300
Annual Direct Operations and Maintenance Cost ($/kW)	$10.00
Money Value - Current or Constant (Dollar Year)	2008
Project Construction or Installation Cost	$18,929
Local Spending	$14,394
Total Annual Operational Expenses	$2,142
Direct Operating and Maintenance Costs	$25
Local Spending	$19
Other Annual Costs	$2,117
Local Spending	$0
Debt Payments	$0
Property Taxes	$0

Local Economic Impacts - Summary Results

During construction and installation period	Jobs	Earnings $000 (2008)	Output $000 (2008)
Project Development and Onsite Labor Impacts	0.1	$2.6	$4.9
Construction and Installation Labor	0.0	$0.9	
Construction and Installation Related Services	0.0	$1.6	
Module and Supply Chain Impacts	0.1	$5.2	$12.6
Induced Impacts	0.0	$2.0	$4.0
Total Impacts	**0.2**	**$9.8**	**$21.6**

During operating years	Annual Jobs	Annual Earnings $000 (2008)	Annual Output $000 (2008)
Onsite Labor Impacts			
PV Project Labor Only	0.0	$0.0	$0.0
Local Revenue and Supply Chain Impacts	0.0	$0.0	$0.0
Induced Impacts	0.0	$0.0	$0.0
Total Impacts	**0.0**	**$0.0**	**$0.0**

Notes: Earnings and Output values are thousands of dollars in year 2008 dollars. Construction and operating period jobs are full-time equivalent for one year (1 FTE = 2,080 hours). Economic impacts "During operating years" represent impacts that occur from system/plant operations/expenditures. Totals may not add up due to independent rounding.

Detailed PV Project Data Costs ARIZONA

Installation Costs	Cost	Purchased Locally (%)	Manufactured Locally (Y or N)
Materials & Equipment			
Mounting (rails, clamps, fittings, etc.)	$183	100%	N
Modules	$8,213	100%	N
Electrical (wire, connectors, breakers, etc.)	$183	100%	N
Inverter	$913	100%	N
Subtotal	$9,490		
Labor			
Installation	$913	100%	
Subtotal	$913		
Subtotal	$10,403		
Other Costs			
Permitting	$183	100%	
Other Costs	$1,825	100%	
Business Overhead	$5,840	100%	
Subtotal	$7,848		
Subtotal	$18,250		
Sales Tax (Materials & Equipment Purchases)	$679	100%	
Total	$18,929		

PV System Annual Operating and Maintenance Costs	Cost	Local Share	Manufactured Locally (Y or N)
Labor			
Technicians	$14	100%	
Subtotal	$14		
Materials and Services			
Materials & Equipment	$11	100%	N
Services	$0	100%	
Subtotal	$11		
Average Annual Payment (Interest and Principal)	$2,117	0%	
Property Taxes	$0	100%	
Total	$2,142		

PV System Annual Operating and Maintenance Costs	Cost	Local Share	Manufactured Locally (Y or N)
Labor			
Technicians	$14	100%	
Subtotal	$14		
Materials and Services			
Materials & Equipment	$11	100%	N
Services	$0	100%	
Subtotal	$11		
Average Annual Payment (Interest and Principal)	$2,117	0%	
Property Taxes	$0	100%	
Total	$2,142		

Other Parameters

Financial Parameters		
Debt Financing		
Percentage financed	80%	0%
Years financed (term)	10	
Interest rate	10%	
Tax Parameters		
Local Property Tax (percent of taxable value)	1%	
Assessed Value (percent of construction cost)	100%	
Taxable Value (percent of assessed value)	100%	
Taxable Value	$18,250	
Property Tax Exemption (percent of local taxes)	100%	
Local Property Taxes	$0	100%
Local Sales Tax Rate	7.15%	
Payroll Parameters	**Wage per hour**	**Employer Payroll Overhead**
Construction and Installation Labor		
Construction Workers / Installers	$27.49	37.6%
O&M Labor		
Technicians	$25.00	37.6%

Appendix H. Water Use Calculations Used in the Case Studies

Table H.1 U.S. Net Generation by Fuel Type and Cooling Type

Fuel Type	U.S. Net Generation (2008) A	Cooling System Type	% Cooling Type B	% Cooling type by fuel type C = A*B
Coal	49.8%	Once-through	39.1%	19.5%
		Recirculating	48.0%	23.9%
		Cooling pond	12.7%	6.3%
		Dry cooling	0.2%	0.1%
Nuclear	20.3%	Once-through	38.1%	7.7%
		Recirculating	43.6%	8.9%
		Cooling pond	18.3%	3.7%
		Dry cooling	0.0%	0.0%
Oil/gas	18.2%	Once-through	59.2%	10.8%
		Recirculating	23.8%	4.3%
		Cooling pond	17.1%	3.1%
		Dry cooling	0.0%	0.0%
Combined cycle	2.9%	Once-through	8.6%	0.2%
		Recirculating	30.8%	0.9%
		Cooling pond	1.7%	0.0%
		Dry cooling	59.0%	1.7%
Hydro	6.2%			6.2%
Other	2.5%			2.5%
Total				**100%**

Sources:	Column A: Fthenakis & Kim 2010 Column B: NETL 2009
Note:	The percent generation by cooling type for combined cycle plants represents the best estimate based on data reported by power plants in the U.S. to the National Energy Technology Laboratory (NETL). The estimate may be misleading, however, because only 7 percent of combined-cycle power plants in operation reported data to NETL. If all plants were to report data, it is very likely that dry cooling would represent a much smaller percentage of total combined cycle cooling, increasing the average life-cycle water withdrawal for plants in the U.S. (NETL 2009).

Table H.2 Water Withdrawwal and Consumption Factors by Fuel and by Cooling System Type

Fuel	Cooling System Type	Withdrawal factor (gal/MWh)	Consumption factor (gal/MWh)	National %	Annual Withdrawal (gal/MWh)	Annual Consumption (gal/MW)
		A	B	C	D=A*C	E=B*C
Coal steam	Once-through cooling	24800	130	19.47%	4829	25
	Recirculating	600	490	23.90%	143	117
	Cooling pond	16450	432	6.32%	1040	27
	Dry cooling	N/A	N/A	0.00%	-	-
Nuclear steam	Once-through cooling	31500	140	7.73%	2436	11
	Recirculating	1100	620	8.85%	97	55
	Cooling pond	3050	2550	3.71%	113	95
	Dry cooling	N/A	N/A	0.00%	-	-
Oil/gas steam	Once-through cooling	86000	340	10.77%	9266	37
	Recirculating	950	600	4.33%	41	26
	Cooling pond	29900	420	3.11%	931	13
	Dry cooling	N/A	N/A	0.00%	-	-
Natural gas combined-cycle	Once-through cooling	9010	20	0.25%	22	0
	Recirculating	150	130	0.89%	1	1
	Cooling pond	5950	240	0.05%	3	0
	Dry cooling	4	4	1.71%	0	0
Hyrdo		N/A	4490	6.20%	-	278
Other				2.50%	0	0
Total				**100%**	**18,924**	**686**

Sources: Columns A & B: NETL 2009, Fthenakis & Kim 2010

Column C: Table G.1

Note: the withdrawal and consumption factors for the "Other" component of U.S. net generation is most likely not 0 gal/MWh, but we are not certain what the fuel compenets of the "Other" category are so have assumed 0 gal/MWh as a conservative estimate

Table H.3 Water Withdrawals for Hi Desert and Greenfield Projects, by Year

Withdrawal factors		
U.S. grid	18,924	gal/MWh
NGCC	289	gal/MWh
Degradation factor	0.70%	

HI DESERT Annual production (MWh) 22,331

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
U.S. Grid (gallons)	422,598,306	419,640,118	416,702,637	413,785,719	410,889,219	408,012,994	405,156,903	402,320,805	399,504,559	396,708,027	393,931,071	391,173,554	388,435,339	385,716,291	383,016,277	380,335,163	377,672,817	375,029,108	372,403,904	369,797,076	7,912,829,888
NGCC (gallons)	6,442,636	6,397,538	6,352,755	6,308,286	6,264,128	6,220,279	6,176,737	6,133,500	6,090,565	6,047,931	6,005,596	5,963,557	5,921,812	5,880,359	5,839,197	5,798,322	5,757,734	5,717,430	5,677,408	5,637,666	120,633,437

GREENFIELD Annual production (MWh) 2,996

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
U.S. Grid (gallons)	56,697,171	56,300,291	55,906,189	55,514,845	55,126,242	54,740,358	54,357,175	53,976,675	53,598,838	53,223,646	52,851,081	52,481,123	52,113,756	51,748,959	51,386,717	51,027,010	50,669,820	50,315,132	49,962,926	49,613,185	1,061,611,139
NGCC	864,365	858,315	852,306	846,340	840,416	834,533	828,691	822,890	817,130	811,410	805,730	800,090	794,490	788,928	783,406	777,922	772,476	767,069	761,700	756,368	16,184,576

Sources: Withdrawal and consumption factors for the U.S. Grid: Table G.2
Withdrawal and consumption factors for NGCC: Fthenakis & Kim 2010
Degradation factor and annual production: provided by Axio

Note: Assumes that most NGCC plants built after 2010 will use a wet recirculating cooling system. The use of closed-loop systems is likely to be more common in the future due to Clean Water Act provisions and public pressures. It is most likely that dry cooling will represent a small percentage of total combined cycle cooling. (NETL 2009) The calculations included in spreadsheet use withdrawal and consumption factors for a NGCC plant that uses a wet recirculating system.

Table H.4 Water Consumption for Hi Desert and Greenfield Projects, by Year

Consumption factors		
U.S. grid	686	gal/MWh
NGCC	270	gal/MWh
Degradation factor	0.70%	

HI DESERT Annual production (MWh) 22,331

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
U.S. Grid (gallons)	15,311,691	15,204,509	15,098,078	14,992,391	14,887,444	14,783,232	14,679,750	14,576,991	14,474,952	14,373,628	14,273,012	14,173,101	14,073,890	13,975,372	13,877,545	13,780,402	13,683,939	13,588,152	13,493,034	13,398,583	286,699,697
NGCC	6,029,370	5,987,164	5,945,254	5,903,637	5,862,312	5,821,276	5,780,527	5,740,063	5,699,883	5,659,984	5,620,364	5,581,021	5,541,954	5,503,160	5,464,638	5,426,386	5,388,401	5,350,682	5,313,227	5,276,035	112,895,339

GREENFIELD Annual production (MWh) 2,996

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
U.S. Grid (gallons)	2,054,267	2,039,887	2,025,607	2,011,428	1,997,348	1,983,367	1,969,483	1,955,697	1,942,007	1,928,413	1,914,914	1,901,510	1,888,199	1,874,982	1,861,857	1,848,824	1,835,882	1,823,031	1,810,270	1,797,598	38,464,569
NGCC	808,920	803,258	797,635	792,051	786,507	781,001	775,534	770,106	764,715	759,362	754,046	748,768	743,527	738,322	733,154	728,022	722,926	717,865	712,840	707,850	15,146,408

Sources: Withdrawal and consumption factors for the U.S. Grid: Table G.2
Withdrawal and consumption factors for NGCC: Fthenakis & Kim 2010
Degradation factor and annual production: provided by Axio

Note: Assumes that most NGCC plants built after 2010 will use a wet recirculating cooling system. The use of closed-loop systems is likely to be more common in the future due to Clean Water Act provisions and public pressures. It is most likely that dry cooling will represent a small percentage of total combined cycle cooling. (NETL 2009) The calculations included in spreadsheet use withdrawal and consumption factors for a NGCC plant that uses a wet recirculating system.

Table H.5 Water Withdrawals and Consumption for Module Cleaning, by Module Area

Withdrawal/consumption factor	4.4	gal/MWh
Performance ratio	0.8	
Efficiency	13%	
Insolation	2400	kWh/m2/year
Withdrawal/consumption factor	1.098	gal/m2/year

	Area per module	No. of modules	Total area (m2)	Withdrawal/ Consumption Factor (gal/m2/year)	Annual Water Withdrawn/ Consumed (gal)	Lifetime Water Withdrawn/ Consumed
	A	B	C=A*B	D	E=C*D	F=20*E
Hi Desert	1.609	49,565	79,726	1.098	87,558	1,751,168
Greenfield	1.422	16,528	23,498	1.098	25,806	516,119

Sources:	Withdrawal factor: NREL 2002
	Performance ratio, efficiency, and insolation: email correspondence with Dr. H. Chul Kim, 2010
	Area per module and number of modules: provided by Axio
Note:	The withdrawal and consumption rates are the same for PV module cleaning
	Column F assumes a 20 year life

Table H.6 On-site and Upstream Withdrawal Factors for Solar PV Modules, by Module Material

	Withdrawal factor (L/MWh)	Insolation (kWh/m2/yr)	Lifetime (yrs)	Performance ratio	Efficiency	Withdrawal fator (L/m2)	Withdrawal factor (gal/m2)
	A	B	C	D	E	F=A*(B/1000)*C*D*E	G=F*0.2642
Multi-Si on-site	200	1800	30	0.8	13.2%	1,140	301
Multi-Si upstream	1470	1800	30	0.8	13.2%	8,383	2,215
Mono-Si on-site	190	1800	30	0.8	14%	1,149	304
Mono-Si upstream	1530	1800	30	0.8	14%	9,253	2,445
CdTe on-site	0.8	1800	30	0.8	10.9%	4	1
CdTe upstream	575	1800	30	0.8	10.9%	2,708	715
Frame on-site	0	1800	30	0.8	13.2%	0	0
Frame upstream	64	1800	30	0.8	13.2%	365	96
BOS on-site	1.5	1800	30	0.8	13.2%	9	2
BOS upstream	210	1800	30	0.8	13.2%	1,198	316

Source: Fthenakis & Kim 2010

Note: the withdrawal factors for the frame and BOS are based on multi-Si PV

Note: multi-Si and mono-Si refers to multicrystalline and monocrystalline; CdTe refers to cadmium telluride

Withdrawal Factors for the Entire Module (included frame and BOS)

Multi-Si	2931.0	gal/m2
Multi-Si thin film	73.3	gal/m2
Mono-Si	3163.4	gal/m2
CdTe	1131.4	gal/m2

Note: assumes multi-Si thin film module uses on 25g PV material for every 1kg used in a multi-Si non thin film module (Fthenakis & Kim 2010)

Table H.7 Water Withdrawals for PV Module Production, by Module Material and Area

Project	Module material	Area per module	No. of modules	Total area (m2)	Withdr. Factor (gal/m2)	Water withdrawn (gal)
		A	B	C=A*B	D	E=C*D
Hi Desert	Multi-si	1.609	49,565	79,726	2931.0	233,680,365
Greenfield	Multi-si, thin film	1.422	16,528	23,498	73.3	1,721,806

Sources: Columns A & B: information provided by Axio
Column D: Table G.6

Table H.8 Annual and Lifetime Water Savings by Project - Global Water Supply[1]

HI DESERT

	ANNUAL		LIFETIME	
	Water Withdrawal (gallons)	Water Consumption (gallons)	Water Withdrawal (gallons)	Water Consumption (gallons)
U.S. grid	422,598,306	15,311,691	7,912,829,888	286,699,697
Module washing	87,558	87,558	1,751,168	1,751,168
Savings	**422,510,748**	**15,224,133**	**7,911,078,720**	**284,948,529**
NGCC	6,442,636	6,029,370	120,633,437	112,895,339
Module washing	87,558	87,558	1,751,168	1,751,168
Savings	**6,355,078**	**5,941,812**	**118,882,269**	**111,144,172**
Project Savings per MW	**635,508**	**594,181**	**11,888,227**	**11,114,417**

GREENFIELD

	ANNUAL		LIFETIME	
	Water Withdrawal (gallons)	Water Consumption (gallons)	Water Withdrawal (gallons)	Water Consumption (gallons)
U.S. grid	56,697,171	2,054,267	1,061,611,139	38,464,569
Module washing	25,806	25,806	516,119	516,119
Savings	**56,671,365**	**2,028,461**	**1,061,095,020**	**37,948,450**
NGCC	864,365	808,920	16,184,576	15,146,408
Module washing	25,806	25,806	516,119	516,119
Savings	**838,559**	**783,114**	**15,668,458**	**14,630,289**
Project Savings per MW	**167,712**	**156,623**	**3,133,692**	**2,926,058**

Sources: Tables G.3, G.4, and G.5

Note: Assumes 20 year project life

Local water supply refers to freshwater sources near a power plant. Approximately 99 percent of thermoelectric power plants in the U.S. rely on local saline or freshwater sources to provide cooling water used to condense the exhaust steam from the turbine-generator (NETL 2009). Although power plants do not consume all of the water withdrawn from the water source, their operation depends on reliable access to a local water supply.

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[1] Local water supply refers to freshwater sources near a power plant. Approximately 99 percent of thermoelectric power plants in the U.S. rely on local saline or freshwater sources to provide cooling water used to condense the exhaust steam from the turbine-generator (NETL 2009). Although power plants do not consume all of the water withdrawn from the water source, their operation depends on reliable access to a local water supply.

Table H.9 Annual and Lifetime Water Savings by Project - Global Water Supply[2]

HI DESERT

	ANNUAL		LIFETIME	
	Water Withdrawal (gallons)	Water Consumption (gallons)	Water Withdrawal (gallons)	Water Consumption (gallons)
U.S. grid	422,598,306	15,311,691	7,912,829,888	286,699,697
Module washing	87,558	87,558	1,751,168	1,751,168
Module manufacturing	-	-	233,680,365	Not available
Savings	**422,510,748**	**15,224,133**	**7,677,398,356**	Not available
NGCC	6,442,636	6,029,370	120,633,437	112,895,339
Module washing	87,558	87,558	1,751,168	1,751,168
Module manufacturing	-	-	233,680,365	Not available
Savings	**6,355,078**	**5,941,812**	**(114,798,096)**	**Not available**
Project Savings per MW	**635,508**	**594,181**	**(11,479,810)**	**Not available**

GREENFIELD

	ANNUAL		LIFETIME	
	Water Withdrawal (gallons)	Water Consumption (gallons)	Water Withdrawal (gallons)	Water Consumption (gallons)
U.S. grid	56,697,171	2,054,267	1,061,611,139	38,464,569
Module washing	25,806	25,806	516,119	516,119
Module manufacturing	-	-	1,721,806	Not available
Savings	**56,671,365**	**2,028,461**	**1,059,373,214**	Not available
NGCC	864,365	808,920	16,184,576	15,146,408
Module washing	25,806	25,806	516,119	516,119
Module manufacturing	-	-	1,721,806	Not available
Savings	**838,559**	**783,114**	**13,946,652**	**Not available**
Project Savings per MW	**167,712**	**156,623**	**2,789,330**	**Not available**

Sources: Tables G.3, G.4, G.5, and G.7

Note: Assumes 20 year project life

Global water supply refers to freshwater sources worldwide. Calculations for global water supply include withdrawals associated with PV module production. These numbers are not included in the local water supply because PV module production and silicon mining/purification does not occur near the majority of solar PV installations in the U.S.

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[2] Global water supply refers to freshwater sources worldwide. Calculations for global water supply include withdrawals associated with PV module production. These numbers are not included in the local water supply because PV module production and silicon mining/purification does not occur near the majority of solar PV installations in the U.S.

References:

Fthenakis, V., and H.C. Kim. "Life-cycle uses of water in U.S. electricity generation." *Renewable and Sustainable Energy Reviews* 14 (2010): 2039-2048.

National Energy Technology Laboratory (NETL). *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements.* National Energy Technology Laboratory, 2009.

National Renewable Energy Laboratory (NREL). *Fuel from the Sky: Solar Power's Potential for Western Energy Supply*. NREL/SR-550-32160, National Renewable Energy Laboratory, 2002.

Appendix I. CO_2 Calculations Used in the Case Studies

Assumptions:

- Natural gas CO_2 emissions factor = 1135 lbs/MWh
- CO_2 emissions factors from specific EPA grid sub-regions vary depending on the electricity generation mix, and were sourced from EPA's EGRID application

Calculation of Emissions:

Generation * Natural Gas Emissions factor - [Emissions from PV generation] = avoided emissions

(MWh/yr) * (lbs. CO_2/MWh)] - [(lbs. CO_2/MWh equiv.)] = avoided emissions

Cost Calculations:

Natural Gas Emissions factor * conversion factor * cost of CO_2 per ton = Cost of avoided emissions

X Lbs/MWh *(X MWh/ yr) * (1 ton/ 2000lbs) * $/ton = $/yr

Cars Calculations:

(Generation * Natural Gas Emissions factor * conversion factor) / (Emissions per U.S. car equiv.)

Appendix J. NO_X Calculations Used in the Case Studies

Assumptions:

- Natural gas NO_X emissions factor = 1.7 lbs/MWh
- NO_X emissions factors from specific EPA grid sub-regions vary depending on the electricity generation mix, and were sourced from EPA's EGRID application

Calculation of Emissions:

Generation * Natural Gas Emissions factor - [Emissions from PV generation] = avoided emissions

(MWh/yr) * (lbs. NO_X/MWh)] - [(lbs. NO_X/MWh equiv.)] = avoided emissions

Cost Calculations:

Natural Gas Emissions factor * conversion factor * cost of NO_X per ton = Cost of avoided emissions

X Lbs/MWh *(X MWh/ yr) * (1 ton/ 2000lbs) * $/ton = $/yr

Cars Calculations:

(Generation * Natural Gas Emissions factor * conversion factor) / (Emissions per U.S. car equiv.)