Potential Impacts of Climate Change on the Energy Sector

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I. Introduction

There is a large body of literature discussing the contributions of the energy sector to global climate change. There is, however, substantially less literature discussing the inverse relationship- the effect of a changing climate on the energy sector itself. Climate change-induced impacts on the energy sector can be classified as direct or indirect. Direct impacts are those that directly effect processes related to fuel production and power generation, including fossil fuel extraction and transportation, energy resource availability, electricity generation, transmission and distribution. Indirect impacts are those whose effects on other sectors generate upstream or downstream impacts on the energy sector, either through competition for shared resources, changes in power demands or requirements, or increased demand for energy intensive activities. Because energy is a basic commodity, used in the production of virtually all other economic goods and services, changes in these other sectors will nearly always cause “ripple effects” for energy. The indirect impacts of climate change on energy, through its effects on the residential, commercial, industrial, and transportation sectors, may in many cases exceed the direct effects. For this reason they cannot be ignored in any assessment of the impacts of climate change on energy.

This paper explores the available literature discussing implications of climate change on the energy sector, both directly and indirectly through other sectors. The paper also includes a discussion of the potential applicability of NETL’s R&D programs to alleviating some of the negative impacts of climate change on energy. The report begins (in Chapter II) with a discussion of the direct effects on the energy sector, and proceeds (in Chapter III) with a review of indirect effects through the agriculture, residential/commercial, industrial and transportation sectors. For these sectors, areas of possible impact on the energy sector are identified by climate change risk; given the particularly synergistic nature of climate change impacts on the agriculture sector, the discussion of the agriculture sector also includes an overview of the cumulative effects of climate change on agriculture and their implications for the energy sector.

The potential impacts on the energy sector are numerous and varied, and so intertwined with economy-wide impacts, that merely identifying the second and third order effects, let alone quantifying them, is difficult. The difficulties are compounded by the high degree of uncertainty surrounding projections of basic climate variables, such as temperature and precipitation. Nonetheless, numerous authors have explored many of these effects individually, and have begun exploring the interactions between climate change-induced impacts in different sectors and the energy sector. Given the complexities, it is safe to say that an attempt to conduct a definitive, comprehensive *analysis* of all of the potential impacts of climate change on the electricity sector is premature at this point in time. That said this paper attempts as comprehensive an *identification* of potential climate-energy interactions as possible. Since there are a number of areas of interaction that are not discussed in the literature, RDS undertook to provide its own identification of potential climate impacts on energy where necessary, along with a limited discussion of these impacts. However, more detailed discussion is limited to impacts for which there exists a substantial body of literature.

Many of NETL’s R&D program initiatives, such as the Innovations for Existing Plants program and the Modern Grid Initiative, are likely to offer significant added value towards future efforts to adapt to and reduce the negative climate change impacts discussed in this report. Chapter IV of the report includes an exploration of the implications of the broader findings of the report for NETL's various R&D programs, and a consideration of how these specific programs may increase the energy sector's ability to adapt to climate change. The discussion is based on conversations with NETL and RDS experts in the subject technologies, further review of the available literature, and inferences drawn by the authors. The resulting analysis of the potential adaptive value of NETL's R&D programs is primarily qualitative in nature. However, detailed recommendations for further analyses aimed at providing a quantitative assessment of the adaptive value of the programs are provided in Chapter V of the report. In addition to the recommendations for further work, Chapter V also includes a summary of the material in Chapters II through IV.

II. Direct Impacts of Climate Change on the Energy Sector

The preponderance of literature addressing the energy sector and climate change is focused on the energy sector's contributions to climate change through emissions of greenhouse gas emissions. There are, however, many ways in which the energy sector itself is vulnerable to the effects of global climate change, as many different aspects of the energy industry- from fossil fuel extraction to electricity generation- are directly affected by environmental and climactic conditions. A brief list of the more pronounced of these interactions is provided below.

- Changes in temperature and precipitation affect water availability for thermal power generators
- Seasonal and daily temperatures and precipitation changes affect the timing of snowmelt, peak/offpeak electricity demands, water availability for cooling and for hydro generation
- Reduced water availability for hydropower generators
- Elevated temperatures generally reduce cooling and generating efficiencies at thermal power plants
- Changes in cloud cover, wind resources, and growing seasons on renewable resources (e.g. changes in renewable resource availability or productivity)
- Impact of sea level changes on existing energy infrastructure (e.g., power plants, transmission lines, refineries, oil and gas pipelines, LNG facilities, etc.) and new infrastructure siting options
- Rises in temperature either increasing or decreasing access to fossil fuel resources (e.g. decreased permafrost driving season in high latitudes, increased supply of oil and natural gas from the Arctic regions as the overlain permafrost melts)
- Impact of changes in storm frequency/intensity on energy infrastructure (e.g., oil and gas drilling, pipelines and refineries in and around the Gulf of Mexico, power lines throughout the world), continuity of energy supply, and energy price volatility due to weather-related supply disruptions
- Increased 'line losses' from electrical transmission and distribution systems due to elevated average temperatures, as well as increased occurrence of blackouts resulting from line sagging during heat waves, all of which are exacerbated by the increased internal resistance heating attributable to increased power flow to meet higher electricity demand for space cooling and refrigeration.[1]

Some of these topics have received considerable attention and research on their own; the body of literature that addresses these issues collectively in the greater context of overall effect on and interactions with the energy sector, however, is relatively new, with little done in the way of quantitative analysis. A 1989 U.S. EPA Report to Congress[2] suggests that climate change had never been considered in power sector planning prior to 1990, when it recommends that "Utility executives and planners should begin to consider climate change as a factor in planning new

[1] It should be noted that other transmission and distribution equipment besides the cables themselves may be adversely affected by heat. For example, transformers may overheat during heat waves.

[2] Kenneth Linder, Chapter 10 – Electricity Demand, *The Potential Effects of Global Climate Change on the United States*, Report to Congress, 1989, http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR5CKPM5/$File/effects_8-13.pdf.

capacity and future operations." A Canadian study reports that few, if any, studies examine the effects of climate change on power supply infrastructure, such as generation facilities and electrical lines.[3] The proceedings of the 2006 World Meteorological Organization (WMO) conference "Living with Climate Variability and Change" identified the need for integrated energy modeling that incorporates energy supply and demand and climate/weather.[4] Recent research by the OECD that evaluated developed countries' progress on assessment and implementation of adaptation to climate change identified only two examples of national communications that included any mention of energy within the context of adaptation.[5] Specifically, the third National Communication of France, identified national guidance on regional planning activities and tools that are "synergistic with adaptation" (the planning tools are to cover energy among the specified policy sectors), and the first National Communication of Belarus describes water resource vulnerabilities, noting likely impacts on hydroelectricity production.[6]

With these limitations in mind, the following sections address the main *direct* impacts of climate change on energy that are considered in the literature published to date. Where applicable, efforts to incorporate them into "bigger picture" energy sector analyses are also identified and discussed.

Reduced water availability for hydropower generators

Multiple reports have identified hydroelectric generation around the world as highly vulnerable to climate change. Hydroelectric power generation depends on stream flow, which depends directly on precipitation and temperature levels. Precipitation directly impacts runoff levels and stream flows which then determines amount of water available for hydroelectric generation. Higher temperatures result in decreased snowpack accumulation, earlier snowpack melt, and increased water evaporation, all of which can reduce water availability for hydroelectric plants. Changes in precipitation cycles due to climate change can alter river flow patterns, resulting in longer periods of drought that decrease rivers' minimum water levels and hydroelectric generation capacity. Another potential consequence of altered river flow patterns is increased incidence of elevated flow rates and flooding that exceed the safety margins of existing hydro plants.

On the other hand, increased flow rates, if timed correctly, might result in increased hydropower generation. For example, a shift in higher stream flow rates from spring to winter (due, e.g., to

[3] Mohammed Dore and Ian Burton, "A Review of the Literature on the Costs of Adaptation to Climate Change," *The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions*, First Deliverable, CCAF Grant # A 209, November 15, 2000, http://adaptation.nrcan.gc.ca/app/filerepository/E74BFBF66A704A778C4D1AD4A8C4BFC2.pdf.
[4] Conference documents, "Living with Climate Variability and Change," World Meteorological Organization (WMO), Finnish Meteorological Institute (FMI), and International Research Institute for Climate and Society (IRI), July 17-21, 2006, Espoo, Finland.
[5] OECD, *Progress on Adaptation to Climate change in Developed Countries, An Analysis of Broad Trends*, Frédéric Gagnon-Lebrun and Shardul Agrawala, May 2006, http://www.oecd.org/document/34/0,2340,en_2649_34359_37178786_1_1_1_1,00.html.
[6] OECD, *Progress on Adaptation to Climate change in Developed Countries, An Analysis of Broad Trends*, Frédéric Gagnon-Lebrun and Shardul Agrawala, May 2006, http://www.oecd.org/document/34/0,2340,en_2649_34359_37178786_1_1_1_1,00.html.

less snow and more rain, or earlier snow melt) may increase hydropower generation more in the winter than it is reduced in the spring and summer. However, there remain questions as to whether existing hydropower plants would be able to take full advantage of increased winter flows, and whether storage systems would be adequate to deal with the increased winter flows. Hydropower plants are generally designed to operate within specific river flow parameters, plus or minus a margin of safety. Climate change leading to river flow changes outside the margin of safety can have a negative impact on hydropower generation, regardless of whether the flow rate increases or decreases.[7]

There are numerous studies that explore the potential consequences of climate change on hydropower productivity in diverse locations- an overview of the conclusions of a select set of these studies is provided in Table 1. Note that the change in hydropower potential resulting from climate change is expected to be positive for some rivers (e.g., the Indus) and negative for others (e.g., the Colorado).

Table 1- Examples of potential changes in annual hydropower generation potential resulting from climactic changes[8]

Region/River	Δ Temperature	Δ Precipitation	Δ Hydropower Generation Potential
Nile River*	+4.7°C	+22%	-21%
Indus River*	+4.7°C	+20%	+19%
Colorado**	+2.0°C	-20%	-49%
New Zealand***	+2.0°C	+10%	+12%

Sources: *Reibsame *et al* (1995),[9] **Nash and Gleick (1993),[10] ***Garr and Fitzharris (1994)[11]

It must be emphasized that significant uncertainties surround assessments of the impact of climate change on hydropower. These uncertainties are, in part, a reflection of underlying uncertainties in the regional precipitation projections of climate models. One of the most comprehensive assessments of the impacts of climate change in the United States is the "National Assessment of the Potential Consequences of Climate Variability and Change" performed by the US Global Change Research Program, the purpose of which was to "…synthesize, evaluate, and report on what we presently know about the potential consequences of climate variability and change for the US in the 21st century."[12] Although the report surveys the results from a wide variety of modeling outputs, it relies primarily on the modeling efforts of

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[7] IPCC, "Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability," 2001, Section 7.3.1.
[8] Table adapted from: Harrison, G. and Whittington, H. "Impact of climactic change on hydropower investment." 2001. Proceedings of the 4th International Conference on Hydropower Development. Bergen, Norway. Available at: http://www.see.ed.ac.uk/~gph/publications/Hydro01.pdf. Accessed 18/6/07,
[9] Reibsame, W., Strzepek, K., Wescoat Jr., J., Perritt, R., Gaile, G., Jacobs, J., Leichenko, R., Magadza, C., Phien, H., Urbiztondo, B., Restrepo, P., Rose, W., Saleh, M., Ti, L., Tucci, C., Yates, D. "Complex River Basins." 1995. In: Strzepek, K.M. & Smith, J.B. (Eds), *As Climate Changes: International Impacts and Implications*. Cambridge University Press.
[10] Nash, L., Gleick, P. "The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation." 1993. US EPA. Washington D.C.
[11] Garr, C. and Fitzharris, B. "Sensitivity of mountain runoff and hydro-electricity to changing climate." 1994. In: *Mountain Environments in Changing Climates.* M. Beniston, (Ed.). Routeledge, London, U.K.
[12] USGCRP. "National Assessment of the Potential Consequences of Climate Variability and Change." 2001. Available at: http://www.usgcrp.gov/usgcrp/nacc/default.htm. Accessed 5/23/07.

the UK's Hadley Centre and the Canadian Centre for Climate Modeling and Analysis for projections of changes in climate. The overarching findings from these assessments with regard to changes in precipitation patterns, (as described in the report) are summarized in Table 2.

As Table 2 indicates, there are significant differences between the Canadian and Hadley models not only in the magnitude, but even the direction, of precipitation change in some regions (e.g., Northeast, Southeast). However, both models agree that large portions of the West and Pacific Northwest will experience reduced water availability. This projection is particularly significant, given that water resources are already stressed in many parts of the West, and hydropower is a major generation source especially in the Northwest. The implications of the climate projections for different western States and localities nonetheless remain uncertain, due in part to the challenges associated with determining the hydrologic impacts of precipitation changes. For example, in a 2003 study for the California Energy Commission (CEC),[13] the Electric Power Research Institute (EPRI) evaluated the potential impacts of climate change on California water resources and reported that hydropower generation could increase or decrease depending on the assumptions defined in the modeled scenario about changes in water runoff from the mountains.

While uncertainties surround the climate and hydrologic forecasts for the western U.S., the current projections nonetheless suggest increased stress on limited water supplies. A sense of the potential impacts of *future* reductions in western U.S. water resources can be gleaned through a consideration of historical droughts and their impacts. SAIC prepared a report for NETL in November 2005 on the impact of climate variability and change on the U.S. power sector.[14] The report included historical case studies of the Pacific Northwest and the Lake Powell/Glen Canyon Dam area, both of which have experienced severe, long-term droughts that have had an effect on regional power generation capacity and plant operation. The report documents the specific effects of prolonged drought on the electricity sector in these regions. For example, the Pacific Northwest case study reveals the vulnerability not only of hydropower producers, but of industries dependent on low-cost hydropower, to long-term drought. In the early part of this decade, drought conditions in the region necessitated a reduction in hydropower generation, which in turn led to higher fuel and electricity prices. The region's aluminum industry, which is heavily dependent on low-cost hydropower, was forced to significantly curtail production in the face of higher electricity prices. The aluminum companies had long-term power contracts with the Bonneville Power Administration (BPA), and in response to the higher electricity prices they sold the power they had already purchased back to BPA in exchange for not operating the smelters. This reduced electricity demand, thereby helping the region to adapt to the effects of reduced hydropower generation and ensuring power was available for core consumers. Of course, this adaptive response came at a significant cost to the regional economy in terms of lost production and revenue.[15]

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[13] Electric Power Research Institute *et al.*, "Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy," Prepared for the California Energy Commission, Public Interest Research Program, 500-03-058CF, August 2003, http://www.energy.ca.gov/pier/final_project_reports/500-03-058cf.html.
[14] SAIC. "Impact of Climate Variability and Change on U.S. Power Sector, Regional Case Studies, Final Report." November 23, 2005.
[15] Ibid., p. C-11.

Table 2- Summary of projected changes in precipitation patterns in the United States on a regional basis.

Region	Projected overall precipitation change by 2100		Additional notes
Northeast (ME, MA, VT, NH, RI, CT, NY, NJ, PA, DE, MD, WV)	Hadley	+ 25% Greatest increases in Western states in summer, New England states in winter	-Decreased drought probability
	Canadian	- 5-10% -Most decreases in Mid-Atlantic, summer & winter	-Increased drought probability -Small, localized regions showing increases
Southeast (AL, FL, GA, KY, LA, NC, MS, SC, TN, East TX)	Hadley	+ 20% -Relative decrease in rainfall in the first half of the year, increasing substantially during the second half of the year.	-High uncertainty in projections for precipitation changes through 2100.
	Canadian	- 10%	-High uncertainty in projections
Midwest (IA, IL, IN, MI, MN, MS, OH, WI	Hadley	+ 20-40% -Increases in maximum daily precipitation amounts	-Slight decrease in drought frequency/intensity
	Canadian	+ 20-40% (Upper Midwest) -20% (Ohio River Valley) -Increases in maximum daily precipitation amounts forecasted	-Increase in drought frequency/intensity
Great Plains (CO, KS, MT, ND, NE, OK, SD, TX, WY)	Hadley/ Canadian	+ 13% -Winter precipitation increases slightly greater than summer increases	-Projected soil moisture decline for most of the region -Greatest precipitation increase in northern, eastern portion, slight decreases predicted in lee of Rockies
West (AZ, CA, Western CO, NM, NV, UT)	Hadley/ Canadian	-Doubling of winter precipitation in California -Slight summer precipitation decreases possible near Rockies	-Increase in flooding probability -Large portions of the West expected to increase dryness through 21st century.
Pacific Northwest (ID, OR, WA)	Hadley	+ 2.5% (2050) -Winter precipitation increases are significantly greater than summer increases	-Overall water availability expected to decline
	Canadian	+ 4.1% (2050) -Winter precipitation increases are significantly greater than summer increases	-Overall water availability expected to decline

In the Lake Powell/Glen Canyon Dam area, prolonged drought over the last decade has resulted in a reduction in hydropower generation, which together with increasing electricity demand has forced an increased reliance on natural gas fired generation. Demand in the region has grown 32 percent, from 157 BKWH in 1990 to 207 BKWH in 2002. Natural gas fired electricity generation has increased five fold in the same time-period, from around 6.5 BKWH to over 31 BKWH. Over the past five years only, natural gas fired generation has almost tripled in the region. Increased reliance on natural gas, and to some extent other sources such as coal-based thermal generation, may be a viable option for meeting increased demand, but could be an expensive option given the likelihood of a continuation in the trend towards of higher natural gas prices (at least until new Liquefied Natural Gas import terminals are sited) in the country. In addition, availability of water to cool thermal plants may become an issue.[16]

In addition to detailing the impacts of the droughts in the case study regions, the SAIC study describes historical steps power planners have taken to mitigate these effects, as well as the regions' adaptation plans for future extreme climactic conditions. Table 3 highlights some of the past and planned future adaptive steps for the Pacific Northwest. It should be noted, however, that the indirect impacts of some of these practices may limit their potential as long term adaptation measures. Actions leading to increased fish mortality at hydropower plants, for instance, are likely to be met with opposition from both indigenous and environmental groups, while reduced power exports would necessitate increased power generation, or a reduction in electricity consumption, within the importing region(s).

Table 3- Power planner responses and adaptation measures to prolonged droughts in the Pacific Northwest

Measures to mitigate effects of existing droughts	-Reduce exports of power outside the region -Increase generation from thermal power plants, including distributed diesel generators -Increase power imports from neighboring regions (when available) -Reduce fish operations at hydropower dams to maximize output -Delay planned outages at thermal plants
Measures to adapt to future droughts	-Relying on more detailed climate projections to determine water management practices -Investing in conservation measures, including incentive programs for end-use efficiency -Identifying and removing constraints in transmission infrastructure -Constructing new transmission lines to reduce inefficiency in power transmission

The impact of climate change on water resources is of particular concern for countries either highly dependent on hydropower, or seeking to increase the role of hydropower in their power sectors. This situation is well illustrated by the case of Belarus, a country that is highly dependent on fuel and electricity imports from neighboring countries. In 2004, 87 percent of Belarus' 31,211 GWh of power generation came from natural gas-fired generators. In the same

[16] Ibid., p. C-19.

year, 98 percent of Belarus' natural gas supply came from imported sources, primarily Russia.[17] Belarus is also dependent on its neighbors to meet its electricity needs; in 2008, Belarus expects to import 5,000 GWh from Russia, and another 2,000 GWh from Ukraine.[18] In light of recent fluctuations in the price of gas and electricity coming from Russia and Ukraine,[19] Belarus is exploring options to expand its relatively small base of hydroelectric generators, which accounted for less than one percent of total electricity generation in 2004.[20] The first National Communication of Belarus describes hydroelectricity production vulnerabilities to climate change. As a result of the vulnerabilities and potential impacts, Belarus prioritized the water resource sector for adaptation and has begun to identify proactive measures. Going a step further than most nations and organizations in their adaptation efforts, Belarus has already developed "a priority list of possible assessments to guide adaptation decisions."[21] Listed priorities range from comprehensive assessment of vulnerability of five rivers to the establishment of a common information-exchange system with neighboring states to assess water resources.

As reflected in the varied results from the studies described above, the implications of climate change on hydropower resources depend on both the hydrologic and design characteristics of the location/hydro plant in question. While there appear to be no studies that explore the cumulative impacts of climate change on hydroelectric generating capacity at the global scale, IPCC infers that generating capacity will decrease at most major hydropower production sites in the world,[22] resulting in an overall increase in the need for thermal electric generation. This, in turn, would have primarily negative implications both for future carbon emissions and for the price of electricity and fossil fuels.

Decreased availability of cooling water resources for electricity generation

Thermal electric power plants- including both nuclear and fossil-fired power plants- are vulnerable to climate change due to their reliance on water for cooling systems. Changes in water availability due to climate change-induced changes in local hydrology, or increased competition for water resources from the commercial/residential or agricultural sectors, could reduce the quantity of water available to power generators. Due to the highly regional nature of water resources and demands, global trends in water availability are difficult to predict, though the IPCC (2001) concludes that globally, water stresses will increase, most notably in Southern and Western Africa and the Middle East, with decreases in stress in parts of Asia.[23] As part of

[17] IEA. "Energy Statistics: Belarus." Available at: http://www.iea.org/Textbase/stats/countryresults.asp?COUNTRY_CODE=BY. Accessed 10/15/07.

[18] Belarusian Telegraph Agency. "In 2008, Belarus to import 5bn kWh of electrical power from Russia, 2bn kWh from Ukraine." 10/16/07. Available at: http://www.belta.by/en/print?id=180712. Accessed 10/17/07.

[19] Neman Environment. "Belarus electricity producers plan to build dams on the river Neman." 5/19/05. Available at: http://www.nemanenvironment.org/index.php?ilist=15. Accessed 10/17/07.

[20] IEA. "Energy Statistics: Belarus." Available at: http://www.iea.org/Textbase/stats/countryresults.asp?COUNTRY_CODE=BY. Accessed 10/15/07.

[21] OECD, *Progress on Adaptation to Climate change in Developed Countries, An Analysis of Broad Trends*, Frédéric Gagnon-Lebrun and Shardul Agrawala, May 2006, http://www.oecd.org/document/34/0,2340,en_2649_34359_37178786_1_1_1_1,00.html.

[22] IPCC. "Third Assessment Report- Impacts, Adaptation and Vulnerability." 2001. http://www.grida.no/climate/ipcc_tar/wg2/368.htm. Accessed 5/28/07.

[23] IPCC. "Third Assessment Report- Impacts, Adaptation and Vulnerability." 2001. http://www.grida.no/climate/ipcc_tar/wg2/368.htm. Accessed 6/18/07.

its “Water 2025” initiative, the U.S Department of the Interior has identified areas of potential water conflict in the Western US by 2025, and identified strategies to avoid conflicts and crises in the future.[24]

The 2005 SAIC study discussed in the preceding section found that “thermal plants are less susceptible than hydroelectric plants to variability in water supplies. Nevertheless, drought can limit access to water supplies. For example, electric generation may have to be curtailed due to higher water temperature (i.e. reduced cooling capacity of water). In year 2002, the intake-water temperatures at several Southeast U.S. plants were too high for effective cooling which resulted in reduced output. Similarly, reduced water levels caused by drought and compounded by summer heat waves throughout Europe in the summer of 2006 forced numerous nuclear plants in France, Spain and Germany to reduce output and, in some cases, be taken offline.[25] Droughts can also necessitate reductions in water used for cooling at thermal power plants. At the same time, thermal plants are called upon to increase their generation during droughts, in order to make up for lost generation from hydropower plants. Thermal plants can use groundwater, surface water or even reclaimed municipal wastewater for cooling purposes, all of which are impacted by drought conditions. Roughly 40 percent of the freshwater used in the United States runs through thermal electric plants, fossil-fueled or nuclear, most of it for cooling purposes. This is by far the largest freshwater use in the eastern United States.”[26]

In the Eastern United States, thermal power generation is a major source of water consumption and thermal pollution. Within the East the Ohio River Basin is an area of particular concern, because 5 nuclear power plants and nearly 50 coal-fired plants are located in the Basin. Although highly uncertain, projections from the Canadian Centre for Climate Modeling and Analysis indicate that precipitation in the Ohio River Valley may decline by 20 percent as a result of climate change—a possibility that could significantly constrain the amount of water available to current and future power plants operating in the valley.

A 1989 U.S. EPA Report to Congress[27] asserted that “lower streamflow and lower lake levels could cause power plants to shift from once-through to evaporative cooling. New plants may also locate in coastal areas to obtain a water source that is reliable and that may be used without violation of thermal restrictions, although sea level rise could be a problem for such plants. This would have important implications for land use, transmission lines, and the costs of power.” Cooling system designs include once-through cooling, which discharges cooling water, at higher temperatures, back to water sources, and evaporative (re-circulating) cooling, which uses cooling towers and ponds. Once-through cooling systems are not major water consumers since they discharge the water after use, but the discharged water has a higher temperature than the surface water (thermal pollution). Relative to once-through cooling, evaporative re-circulating cooling systems increase water consumption (with less need for makeup water) and reduce the quantity

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[24] US Department of the Interior. “ Water 2025: Preventing crises and conflict in the West.” August 2005. Available at: http://www.doi.gov/water2025/ppt.html. Accessed 6/24/07.
[25] Sachs, S. “Nuclear power’s green promise dulled by rising temps.” Christian Science Monitor. 8/10/06. Available at: http://www.csmonitor.com/2006/0810/p04s01-woeu.html. Accessed 10/15/07.
[26] SAIC, Impact of Climate Variability and Change on U.S. Power Sector, Draft Report,
[27] Mark Mugler and Michael Rubino, Chapter 9 – Water Resources, *The Potential Effects of Global Climate Change on the United States*, Report to Congress, 1989,
http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR5CKPM5/$File/effects_8-13.pdf.

of thermally polluted water discharged into their neighboring environment. There is a general trend in the United States to equip plants with re-circulating cooling towers. This trend is consistent with the Federal Water Pollution Control Act (FWPCA) of 1972 (later amended in 1977 by the Clean Water Act). The CWA gave the EPA authority to set effluent standards for all point-source industries, such as power plants, oil, and gas wells. In addition, it is hard to retrofit once-through cooling plants with re-circulating systems because of land issues and costs of conversion.

Proposed adaptation measures include bigger cooling towers or new plant siting close to larger water bodies that can absorb the added heat from cooling water discharge without adverse impacts to the aquatic systems.[28] Another suggested adaptation strategy is to modify nuclear power plants to allow for continued operation in warmer temperatures outside their previous design ranges. In addition, energy infrastructure siting regulations could be reviewed and revised, taking into account future climate change. For example, river-front power plant siting regulations should consider the effects of changes in river flows, and coastal power plants and oil and gas production infrastructure should consider extreme weather events and sea level rise.[29] Dry cooling technology, as well as other technologies under development at NETL which are designed to reduce power plant water requirements, may be key elements of an adaptive strategy.

Impacts of increased temperatures and humidity on thermal power generating efficiency

Changes in a temperature and humidity levels affect the generating efficiency of thermal power generators. As explained in the *UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, "Higher ambient air temperatures will decrease the efficiency and capacity ratings of natural gas or oil fired combustion turbines. Increases in ambient temperatures and humidity will also be detrimental to electricity generation from gas, oil, or nuclear steam cycles, which rely on cooling towers for the condensing process. The overall effect of global warming on thermal electric power production is likely to be small, however."[30]

While overall long-term impacts may be limited, the short-term heat waves in specific regions can threaten significant power supply disruptions. For example, the 2003 and 2006 heat waves in Europe lead to decreased availability of cooling water for electricity generation. Extremely high temperatures in Europe during the summer of 2003 threatened the shut-down of nuclear power plants for lack of cooling water, [31] and again in July 2006, a heat spell across Europe forced several nuclear power plants to reduce generation or shut down to prevent additional impacts on wildlife populations that rely on adjacent rivers used for reactor cooling water. The Santa Maria de Garona reactor in Spain was shut down, more than one reactor in Germany

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[28] Juliette Jowit and Javier Espinoza, "Heatwave shuts down nuclear power plants," The Observer, The Guardian Unlimited, July 30, 2006, http://observer.guardian.co.uk/world/story/0,,1833620,00.html?gusrc=rss&feed=12.
[29] Jan F. Feenstra et al., *UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, Chapter 11 – Energy, Frank Stern, UNEP/IVM, 1998.
[30] Jan F. Feenstra et al., *UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, Chapter 11 – Energy, Frank Stern, UNEP/IVM, 1998.
[31] John Carey, "Business on a Warmer Planet. Rising temperatures and later winters are already costing millions. How some companies are adapting to the new reality," *BusinessWeek online*, July 17, 2006, http://www.businessweek.com/magazine/content/06_29/b3993046.htm.

reportedly reduced operation, and other units in Germany and France were granted special permits to discharge hot water into the rivers to avoid electricity shortages.[32] These water shortage impacts suggest that while nuclear power plants may offer emission reduction benefits, a high level of dependence on nuclear power (as in France) may reduce the power sector's ability to adapt to declines in precipitation.

Impacts on fossil fuel production and distribution activities

Many fossil fuel production and distribution activities are likely to be impacted by climate change. This discussion will focus on two major potential impacts- the role of higher temperatures increasing or decreasing access to fossil resources in northern latitudes, and potential disruptions in production and distribution capabilities caused by extreme weather events. Our focus on these two areas in particular is driven by the available literature; however, it should be noted that many other potential impacts may exist. To take the coal industry as just one example, increased humidity may present coal drying challenges, while more arid conditions may increase the danger of spontaneous combustion. Increased humidity and temperature may also reduce diesel engine efficiencies at surface coal mining operations, while increases in precipitation could pose maintenance and operating challenges at these mines. While the available literature does not address these (and many other) issues, it is important to keep in mind that the impacts that *have* been addressed (and that are considered in more detail below) may well represent only a small fraction of the full range of potential impacts of climate change on fossil fuel production and distribution.

Effect of Increased Temperatures on Exploration and Production Activities in the Arctic

Extreme northern and southern latitudes are likely to be disproportionately impacted by climate change, with many models predicting climate change in the Arctic to be more severe than elsewhere on the globe.[33] In 2004, the Arctic Council and International Arctic Science Committee published an extensive "Arctic Climate Impact Assessment" exploring the potential impacts of climate change on the Arctic region, including impacts on energy resources, access and infrastructure.

In Alaska, one significant impact of warmer temperatures on the oil and gas industries is the shorter season during which exploration and drilling can occur without damage to the tundra. The timeframe for vehicular travel on the tundra has been cut by more than half since 1970, which has had logistical and economic impacts on oil and gas exploration and development.[34] In May 2006, the state legislature of Alaska unanimously passed HCR 30, titled "Creating an Alaska Climate Impact Assessment Commission." The Commission's task is to assess the anticipated climate change impacts on the natural and built environment (including the thawing

[32] Juliette Jowit and Javier Espinoza, "Heatwave shuts down nuclear power plants," The Observer, The Guardian Unlimited, July 30, 2006, http://observer.guardian.co.uk/world/story/0,,1833620,00.html?gusrc=rss&feed=12.
[33] Kattsov, V., Kallen, E. "Arctic Climate Impact Assessment, Chapter 4- Future Climate Change- Modeling and Scenarios for the Arctic." 2004. The Arctic Council. Cambridge University Press. Available at: http://www.acia.uaf.edu/pages/scientific.html. Accessed 6/20/07.
[34] John Carey, "Business on a Warmer Planet. Rising temperatures and later winters are already costing millions. How some companies are adapting to the new reality," *BusinessWeek online*, July 17, 2006, http://www.businessweek.com/magazine/content/06_29/b3993046.htm.

permafrost) as well as social and economic costs, and develop recommendations of reactive mitigation responses and proactive adaptation strategies.[35] Sufficiently short tundra travel seasons could eventually make many exploration and production activities unprofitable, particularly those further away from existing infrastructure.

As discussed in Instanes *et al* (2004)[36] melting of permafrost can also present challenges for oil and gas pipelines that are built on or in permafrost soils, including greater settlement of shallow pile foundations for pipelines built above ground, and greater frost heave and thaw settlement damage for buried natural gas lines. Overall decreases in structural stability can be expected to increase construction and operation costs for pipelines.

Another potential impact of warming weather on arctic environments is the reduction of sea-ice cover, which could have large impacts on exploration activities and for shipping routes through the arctic. As discussed in the Arctic Climate Impact Assessment,[37] retreating sea-ice cover levels can be expected to increase access to Arctic shipping routes; the navigation season (during which sea ice concentration is 50 percent or less) along the Northern Sea Route (NSR) is expected to increase from the existing 20-30 days per year to 80-90 days per year in 2080.

In addition to providing much reduced shipping distances between Northern Europe, Northeastern Asia and Northwestern North America, greater access to the NSR could yield dramatically improved access to the abundant reserves of natural gas and oil in the Russian Arctic. In Alaska, reduced sea-ice could reduce costs and difficulties associated with offshore oil and gas exploration and production activities in Arctic regions, the products of which could possibly be shipped directly from northern ports, obviating the need to link into pipelines connecting to southerly ports, such as the Trans-Alaskan Pipeline. Potential shipping routes and infrastructure are discussed by Sherwood (2006), who also points out that arctic offshore resources account for 79 and 89 percent of Alaskan offshore gas and oil resources, respectively.[38] As discussed in the Arctic Climate Impact Assessment, however, greater shipping access to and through these regions is not a given, as year-to-year variability in ice conditions and the overall quantity of multi-year ice and icebergs in shipping routes may both increase in the future, rendering them more difficult to navigate.[39] Nonetheless, the prospect of

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[35] HCR 30, Creating an Alaska Climate Impact Assessment Commission, http://www.legis.state.ak.us/BASIS/get_bill_text.asp?hsid=HCR030Z&session=24.

[36] Instanes, A. Anisimov, O., Brigham, L., Goering, D., Khrustalev, L., Ladanyi, B., Larsen, O. "Arctic Climate Impact Assessment- Chapter 16- Infrastructure: Buildings, support systems and industrial facilities." 2004. Arctic Council/International Arctic Science Committee. Available at: http://www.acia.uaf.edu/pages/scientific.html. Accessed 6/22/07.

[37] Instanes, A. Anisimov, O., Brigham, L., Goering, D., Khrustalev, L., Ladanyi, B., Larsen, O. "Arctic Climate Impact Assessment- Chapter 16- Infrastructure: Buildings, support systems and industrial facilities." 2004. Arctic Council/International Arctic Science Committee. Available at: http://www.acia.uaf.edu/pages/scientific.html. Accessed 6/22/07.

[38] Sherwood, K. "Petroleum potential of the Arctic Offshore of Alaska." Abstract and powerpoint presentation given to the geophysical society of Alaska. April 2006. Available at: http://www.mms.gov/alaska/re/reports/rereport.htm. Accessed 6/24/07.

[39] Instanes, A. Anisimov, O., Brigham, L., Goering, D., Khrustalev, L., Ladanyi, B., Larsen, O. "Arctic Climate Impact Assessment- Chapter 16- Infrastructure: Buildings, support systems and industrial facilities." 2004. Arctic Council/International Arctic Science Committee. Available at: http://www.acia.uaf.edu/pages/scientific.html. Accessed 6/22/07.

lucrative trade routes, as well as greater access to fossil and mineral resources has already spawned efforts to assert sovereignty over areas of the Arctic that have historically been inaccessible. Such efforts have been undertaken by all five countries with coastline along the Arctic Ocean (Canada, Denmark- via Greenland, Norway, Russia and the United States).[40]

Methane Hydrates. Methane hydrates are a potentially enormous future source of energy. Methane hydrates (also referred to as methane clathrates) are a type of crystalline structure composed of methane gas enclosed by a cage-like lattice of ice, and occur naturally in locations with sufficiently low temperatures and/or high pressures to preserve their structure; they typically occur within sediments underlying permafrost or the ocean floor where pressure and temperature conditions are suitable for stability and where there exists a combined access to both methane and water. As an energy resource, they have potential beneficial greenhouse gas implications for the energy sector; given their global preponderance—estimates of global methane hydrate resources vary significantly, from 100,000 to 3,000,000 trillion cubic feet (Tcf)—should even a small fraction of them prove recoverable, methane hydrates could offset a sizeable share of other, more carbon intensive fossil fuels. Resources in the U.S. are officially estimated at 320,000 Tcf, based on an appraisal conducted by the U. S. Geological Survey in 1995. More recent results from the National Science Foundation's Ocean Drilling Program, reviewed by Advanced Resources International (ARI), however, suggest the figure may be closer to 200,000 Tcf.[41] Of that estimated domestic hydrate resource, approximately half are situated offshore of Alaska.[42] In the short term, deposits located beneath Alaskan and Northern Canadian permafrost are the most likely to prove economically viable for production of natural gas from hydrate. In addition to a host of engineering challenges unique to them, the considerations regarding the potential impacts of climate change on the exploration and production of conventional fossil fuels, discussed above, should also apply to methane hydrates.

However, beyond these considerations there is another issue that is unique to methane hydrates. Given their sensitivity to temperature and pressure, it is possible that significant increases in the atmospheric temperatures, leading to eventual subsurface temperature changes of the environment containing hydrate (e.g. sub-permafrost sediment) could potentially lead to dissociation of methane from the hydrate structure, thereby mobilizing a portion of the methane to a free gas form. In this free gas form, the methane could move within the subsurface sediment and potentially escape to the atmosphere over time if gas venting pathways exist or are created within the hydrate containing areas. This could result not only in the redistribution or even loss of potentially valuable energy resources but, more importantly, it could contribute to further climate change were the gas from dissociating hydrate to reach the atmosphere. As discussed in Archer (2007),[43] although there is considerable uncertainty regarding the overall stability of global hydrate reservoirs, it appears relatively unlikely that these reservoirs will undergo

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[40] Reid, T. "Arctic military bases signal new Cold War." The Times Online. August 11, 2007. Available at: http://www.timesonline.co.uk/tol/news/world/us_and_americas/article2238243.ece. Accessed 10/15/07.

[41] Advanced Resources International, Inc. "Review of non-technical issues relating to commercial methane hydrate production, final report for DOE/NETL." September 2004. Available at: http://www.netl.doe.gov/technologies/oil-gas/publications/AP/hydrates%20imped%20study_final.pdf. Accessed 10/11/07.

[42] USGS. "Natural gas hydrates: Vast resources, uncertain future." March 2001. Available at: http://pubs.usgs.gov/fs/fs021-01/fs021-01.pdf Accessed 6/26/07.

[43] Archer, D. "Methane hydrate stability and anthropogenic climate change." 2007. Biogeosciences Discussions. Available at: http://geosci.uchicago.edu/~archer/reprints/archer.2007.hydrate_stab.pdf. Accessed 6/27/07.

significant temperature-related changes that would result in significant methane release due to hydrate dissociation on timescales of less than a millennium.

Canadian oil sands and water availability. Canada's oil sands present another example of the potential impact of climate change on the extraction of fossil fuel reserves at high northern latitudes. Alberta's oil sands, located in three main deposits in northern Alberta covering an area larger then the state of Florida, contain over 170 billion barrels of proven reserves.[44] Unlike methane hydrates, however, these enormous oil reserves are being developed today. In fact oil sands production is increasing rapidly, a trend that is expected to continue for the foreseeable future. Extracting oil from the viscous bitumen is a water-intensive process (between 2 to 4 barrels of water are required per barrel of oil produced). Assessments of climate change in the region project decreased water flow in the Athabasca River, raising concerns that water resources might limit production from oil sands over time. The interaction between climate change, competing water use demands and requirements of the burgeoning oil sands industry are currently being explored by Natural Resources Canada.[45]

Impact of extreme weather events on oil and gas production and distribution

Many sources predict that climate change will result in the increased incidence of extreme weather events, including the frequency of severe storms.[46,47,48] Home to some 30 percent of the nation's crude oil production capacity, 20 percent of natural gas production capacity, and 45 percent of total refining capacity,[49] the Gulf of Mexico is probably the location most vulnerable to damages from hurricanes and severe storms. As was most recently illustrated by Hurricanes Rita and Katrina in 2005, severe storms can have dramatic impacts on the region's energy production and distribution infrastructure and energy prices throughout the country. By destroying 115 platforms, damaging over 180 pipelines,[50] and causing direct losses to the energy industry estimated at over $15 billion with substantial additional restoration and recovery costs, Hurricanes Rita and Katrina triggered fuel price spikes throughout the United States.[51] In

[44] "Oil Sands." Alberta Government website. http://www.energy.gov.ab.ca/89.asp. Accessed 6/26/07.
[45] NRCAN. "Assessing climate change impacts on water availability for tar sands development in the Athabasca River Basin." Natural Resources Canada website. http://ess.nrcan.gc.ca/ercc-rrcc/proj1/theme1/act1_e.php. Accessed 6/26/07.
[46] Emanuel, Kerry. "Increasing destructiveness of tropical cyclones over the past 30 years." 8/4/04. Nature. Available at: ftp://texmex.mit.edu/pub/emanuel/PAPERS/NATURE03906.pdf. Accessed 10/10/07.
[47] Diffenbach, N. "Sensitivity of extreme climate events to CO2-induced biophysical atmosphere-vegetation feedbacks in the western United States." Geophysical Research Letters. April 5, 2005. Available at: http://www.purdue.edu/eas/earthsystem/Diffenbaugh_GRL_05.pdf. Accessed 10/10/07.
[48] Trenberth, K., D. Shea. "Atlantic hurricanes and natural variability in 2005," Geophysical Research Letters. June 27, 2006. Available at: http://www.cgd.ucar.edu/cas/trenberth.pdf/TrenberthSheaHurricanes2006GRL026894.pdf. Accessed 10/11/07.
[49] Dismukes, D. "Concentration of Energy Infrastructure in Hurricane Regions." Presentation before the National Commission on Energy Policy. June 21, 2006.
[50] US Department of the Interior Minerals Management Service. "Impact Assessment of Offshore Facilities from Hurricanes Katrina and Rita." January 2006. MMS Press Release. Available at: http://www.mms.gov/ooc/press/2006/press0119.htm. Accessed 22/6/07.
[51] Cohen, S. "Energy sector recasts storm survival plans." June 9, 2006. MarketWatch report. Available at: http://www.marketwatch.com/news/story/can-gulf-coast-energy-industry/story.aspx?guid=%7B6158127A%2DAABF%2D41D3%2D976E%2D25E3C17F28C3%7D. Accessed 6/24/07.

response, Shell, Chevron, the Minerals Management Service officials, the American Petroleum Institute and others began investigating ways of minimizing damages from future disasters, including the development of stricter platform anchoring guidelines and minimum height-above-water standards.[52] Over time, adaptation measures such as more stringent, safer building codes, construction of protective facilities and relocation costs will likely increase construction and operating costs of these facilities.

Impacts on electricity transmission and distribution

Climate change is likely to impact electricity transmission and distribution systems in a variety of ways, with consequences for the future development of the grid. While there appears to be a shortage of literature collectively assessing weather-related impacts in the context of climate change, much can be discerned about them individually.

The term "line loss" refers to the phenomenon by which electricity transmitted over power lines is converted to heat through resistance and lost to the environment. As an electric current passes through power lines, interactions between flowing electrons and the material of the conductive power line raise the kinetic energy of the conductor, which is then transferred to the immediate environment as heat. This phenomenon increases in as a function of the resistance of the conductor, and the square of the current passing through the conductor:

$$\mathbf{E = I^2 r}$$

where:

E	=	energy lost to the environment (joules)
I	=	current passing through the conductor (amperes)
r	=	resistance of the conductor (ohms)

Line losses are exacerbated by both power demand and temperature. Higher demands increase losses by increasing the current flowing through power lines. During high temperatures, the warmer ambient air is less capable of accepting heat radiated from the power lines. Thus, summer peak demands represent the periods when line losses are typically at their highest. In terms of potential impacts on generation requirements, climate change-induced temperature increases can be expected to increase generation requirements over and above increases resulting from growth in demand. As explained by the UNEP/IVM "Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies" states, "…electric transmission lines have greater resistance in warmer temperatures, and thus climate change will result in increased line losses…For a country with 8 percent line losses, a 3^0C temperature increase will cause…an increased need for generation of about 1 percent."[53] Thus, rising temperatures can be expected to increase generation requirements, provided that the safe upper temperature limit of T/D equipment is not exceeded.

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[52]Porretto, J. "Gas prices are certain to climb if season's first storm enters the Gulf of Mexico." May 26, 2007. Associated Press. Available at: http://biz.yahoo.com/ap/070526/hurricanes_oil.html?.v=2. Accessed 22/6/07.
[53] Jan F. Feenstra et al., *UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, Chapter 11 – Energy, Frank Stern, UNEP/IVM, 1998.

In addition to reducing the efficiency of transmission, higher temperatures and higher loads associated with increased cooling demands pose threats to the operational stability of many T/D system components, many of which are designed to operate within certain load and temperature boundaries.   This vulnerability was well illustrated by a heat wave in Southern California in the summer of 2006 that, in conjunction with record-high demand loads, caused thousands of transformers to fail, resulting in rolling power blackouts for thousands of consumers.

Power lines are another portion of the grid that is susceptible to high temperatures; when temperatures exceed optimum conditions, reinforcing steel cables in power lines lose their tensile strength, expand, and begin to sag. Sagging lines can come into contact with otherwise out of the way grounded objects, like tree limbs, and cause electrical shortages. During periods of intense demand- typically when temperatures are high and transmission systems are operating close to their capacity limits, such shortages can trigger much greater system outages, as was seen during the Northeast power blackout of August, 2003. Similarly, transmission and distribution systems are susceptible to damage from extreme weather events. Increased incidences of ice storms, tornados, hurricanes, and other powerful storms are all potential threats to power system security.

Over time, there are a number of ways in which the power sector can adapt to reduce transmission and distribution system vulnerabilities to the above-mentioned threats. Higher efficiency cables, including superconductive cables, could reduce losses and sag vulnerability in certain key transmission lines. In addition, while running power cables underground is more capital-intensive then running them overhead, the greater transmission capacity and reduced losses associated with advanced conductor materials renders them more attractive for underground burial, which would reduce their vulnerability to human and weather-related disturbances.

Distributed generators, remote power storage devices (distributed resources, collectively, or DR) and demand side management (DSM) programs targeted at reducing or shifting loads from end-users during peak demands can all provide relief from shrinking transmission capacity margins and growing peak demands by a) freeing up capacity on T/D systems that would otherwise be used to deliver power from remote generators, and, b) providing “peak shaving” services to help offset increasingly expensive power from peaking power units. It is worth noting, however, how their individual attributes can contribute to increased grid stability. Distributed generators offer the benefit of being able to operate independently of the greater transmission and distribution infrastructure. Provided a constant supply of fuel, they are able to provide continuous power to critical end uses or, in some cases, into smaller regional grid networks in the event of a power outage. Power storage devices offer the same benefit with no emissions, but on a more limited time frame. While DSM actions are not able to provide power during outages, they are generally the most cost effective way of achieving emissions free demand savings. Furthermore, while large-scale adoption of distributed generation and power storage will require major changes to the existing infrastructure, and will therefore take time, DSM and increased utilization of energy efficient products can be implemented quickly.

While many of these technologies offer promising benefits, they are unlikely to entirely replace larger centralized generators, many of which benefit from emissions control technologies that are currently only cost effective at larger scales, including carbon capture and storage systems. As such, they must be designed and implemented in such a way as to work in harmony with centralized generators. Advances in automated control and relay technologies make this coordination possible, and also enable the grid to function much more reactively to unforeseen shifts in load and transmission patterns. An additional benefit of this coordinated approach is to shift loads to centralized generators at times of the day when they are available to meet them. Many of these grid-coordinating systems are discussed in the U.S. Department of Energy's 2002 National Transmission Grid Study.[54]

[54] U.S. DOE. "National Transmission Grid Study." 2002. Available at: http://www.pi.energy.gov/documents/TransmissionGrid.pdf. Accessed 6/23/07

III. Indirect Impacts of Climate Change on the Energy Sector

Agriculture Sector

Overview

Due to the heavily environment-dependent nature of both livestock and crop species, there are many measures through which climate change can impact the agriculture sector. Water availability, atmospheric carbon dioxide-to-oxygen ratios, solar incidence, seasonal patterns and extremes of temperature, and the prevalence of pests and diseases are all determinants of plant productivity, and are all affected by climate variability and change. Electricity and fossil fuels are the two primary forms of energy consumed directly by the agriculture sector, with fertilizer and pesticides accounting for a significant share of indirect energy consumption. As a main driver of energy and water requirements, changes in agricultural productivity largely influence demand for direct and indirect energy inputs. Other important factors include changes in heating and cooling requirements, changes in water demand and availability, and potential changes in the global movement of agricultural products. Interactions between the agriculture and energy sectors are likely to vary significantly between regions, and on a regional and global scale.

Direct Impacts of Climate Change on the Agriculture Sector

Increased atmospheric carbon dioxide levels

Carbon Fertilization

The term "carbon fertilization" refers to the phenomenon by which increased ambient CO_2 levels render CO_2 more available to photosynthesizing plants, thereby increasing overall productivity. However, different species respond differently to increased CO_2 concentrations, based primarily on the type of photosynthetic pathway they employ. Relative to the more common C3 pathway, plants that utilize the C4 and CAM pathways employ physical and chemical mechanisms to better give them an adaptive advantage in warmer and more arid environments; C4 plants chemically fix CO_2 with an intermediary enzyme before transferring it to a specially adapted cell where photosynthesis occurs, while CAM plants fix CO_2 during the cooler night hours, store it as an acid, and then keep their water-losing stomata closed during the day while photosynthesis is performed with stored CO_2. Plants employing the C3 photosynthetic pathway typically respond favorably to increases in CO_2, while plants employing C4 or CAM photosynthetic pathways show much reduced gains in productivity. Examples of economically significant C3 and C4 agricultural crop species are shown in Table 4.

Table 4- Examples of C3, C4 and CAM crop species

C3	C4	CAM
Barley Cotton Potatoes Rice Soybeans Wheat	Maize Millet Sorghum Sugarcane	Cassava Pineapple Onions Castor

C3 crops may also benefit from increased productivity relative to competing weeds. The potential effect of carbon fertilization on increasing or decreasing the performance of weed species relative to crops is also significant, as 14 of the world's 17 most problematic weed species are C4 plants that grow in C3 crops.[55] This benefit may be reversed, however, in C4 crops plagued by C3 weeds.

Overall productivity rates are relevant to the energy sector, as they largely determine the quantities of fertilizers, irrigation, drying, storage, and pesticide requirements of a given crop. In general, increased productivity should reduce the input requirements of these factors per unit of crop yield, though this trend can be expected to be obscured by the various factors contributing to overall yields. For instance, a plant grown in nutrient-optimum conditions in one atmospheric CO_2 concentration may be nutrient-limited in elevated CO_2 levels. Different species will respond differently to increased nutrient application, however, some will increase yields of harvestable material, while others will accumulate starches or show increased biomass accumulation in non-harvestable plant parts (e.g. stalks, leaves). As discussed in this section, the sum of these changes will determine the quantity of energy inputs required on a per-unit-of-yield basis.

Effects on Transpiration and Water-use Efficiency

Another important physiological effect of elevated CO_2 levels on plants is the promotion of stomatal closing. Stomata are the primary source of transpirative water loss; by promoting closure, water loss through transpiration is reduced, thereby reducing water requirements through increased water-use efficiency (WUE). Again, the extent to which this trend occurs varies with species and environment. Changes in WUE (along with changes in precipitation, temperature and runoff rates) contribute to the overall water demands of a given crop, which, in turn, affect the quantity of power required for water pumping as well as the quantity of water locally available for use by power generators. These interactions are discussed more thoroughly below.

[55] Morison, J.I.L. "Plant growth in increased atmospheric CO2", in Fantechi, R. and Ghazi, A. (eds), *Carbon Dioxide and Other Greenhouse Gases: Climatic and Associated Impacts.* 1989. Dordecht, The Netherlands.

Increased temperatures

Effects on Growth Rate/Growing Season

Temperature has a direct effect on the growth rate of plants. In general, growth rate is positively correlated with temperature, up to a threshold after which further temperature increases are detrimental. Temperature is often a limiting factor in agriculture, as it is a determinant of the length of the growing season (e.g. between frosts) and the physiological suitability of different crop species. Increased temperatures can be expected to elicit a variety of effects on crops[56]:

- rising night temperatures will reduce yields of some crops;
- positively impact growth rates of CAM-type crops;
- diminished yield per crop of annual crop, but often allow for multiple crops per season;
- increased productivity at high latitudes/altitudes, and;
- increased pest pressure at high latitudes/altitudes.

Based on their assessment of relevant scientific literature and quantitative modeling analyses of climate change impacts on agriculture in North America, Reilly *et al* (2003)[57] project increased temperatures to expedite crop ripening times for most irrigated species, leading to an overall reduction in water demand and pumping. In general, this trend should contribute to reductions in agricultural demand for electricity for pumping as well as reduce competition between agriculture and energy generators for water resources in water constrained areas.

Livestock grown at the edge of their temperature ranges stand to be negatively affected by temperature increases through increased heat stress and mortality. Summer electricity demand can be expected to increase for facilities that use fans and air-conditioning to manage climates for livestock or greenhouse facilities. On the opposite end of the spectrum, average winter heating demands for heated facilities (e.g. chicken coops, nurseries, greenhouses) should be reduced.

Changes to hydrologic cycle/water availability

In higher temperatures, increased evaporation rates cause soils to lose moisture more quickly—a situation that will be exacerbated in regions where increased temperatures are accompanied by more arid conditions. In addition to evaporation rates, soil moisture is determined by runoff rates and precipitation levels, which are projected to change significantly in many agricultural zones. In a given region, the net change in soil moisture will be determined by the interplay between changes in temperature, precipitation and humidity.

On a larger scale, changes in temperature, evaporation and precipitation patterns will change the hydrologic cycle of a given area, influencing water availability, erosion, nutrient deposition and

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[56] FAO. Global climate change and agricultural production. Direct and indirect effects of changing hydrological, pedological and plant physiological processes. 1996. Rome, Italy.

[57] Reilly, J. Tubiello, B. McCarl, D. Abler, R. Darwin, K. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Learns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg, and C. Rosenzweig, “U.S. agriculture and climate change: New results.” 2003. *Climatic Change*, 57.

leaching and runoff rates. Changes in regional precipitation patterns and amounts stand to significantly alter irrigation and water pumping requirements for agricultural practices. Reilly *et al*'s (2003) modeling results show increased precipitation contributing to increased productivity of dryland crops, and also reducing water demand for irrigated crops.

Changes to climactic variability/extreme weather events

Increased incidence of extreme weather events, including droughts, intense rainfall, extreme hot and cold spells, can significantly affect agricultural productivity through increased mortality, flooding, and damage to crops, livestock and facilities. Damage to energy infrastructure caused by extreme weather events could generate power supply disruptions, which, as discussed in Miranowski (2005), can cause significant losses in agricultural productivity during energy dependent, sensitive periods.

Sea level rise

In its Third Assessment Report, the IPCC projects a global-average sea level rise of 0.7-1.1 meters in the period from 1990-2100.[58] Rising sea levels can affect coastally-situated agricultural areas through salinization of groundwater, estuaries, and soils, coastal erosion and sediment deposition, direct inundation, and an increase in the area of flood-susceptible lands. Land reclamation, seawall construction and additional water pumping requirements are examples of energy-intensive responses to the effects of sea level rise.

Cumulative Effects of Climate Risks to the Agriculture Sector on the Energy Sector

A unified assessment of the overall impact of climate change-induced changes to the agriculture sector on the energy sector is confounded by the wide variety of agricultural regions, the divergent climactic shifts predicted for each, and the myriad responses among different livestock and crop species to those changes. Nonetheless, it is possible to hypothesize on bigger-picture trends based on the more targeted literature that is available.

Change in overall productivity is probably the factor with the single largest potential effect on the agriculture sector's use of energy resources. At the scale of a single agricultural entity or region, productivity is influenced by all of the factors discussed above- changes in temperature, humidity, precipitation, atmospheric CO_2 concentrations, extreme weather events, and sea level rise, all of which will affect direct and indirect energy consumption on a local level. On a global scale, changes in regional productivity can have significant effects on the availability and movement of agricultural products.

In the future, it is likely that more energy will be dedicated to transporting agricultural products from areas of higher productivity to ameliorate food shortages in areas where climactic changes

[58] Contribution of the Working Group III to the Third Assessment Report of the IPCC. "Climate Change 2001: The Scientific Basis." IPCC. 2001. http://www.grida.no/climate/ipcc_tar/wg1/409.htm (Accessed 6/1/07).

will contribute to overall declines in agricultural productivity. Global trends in productivity are explored in a number of sources; examples of publications that explore modeling results of projected productivity changes include the IPCC's Third Assessment Report (2001) [59] and Rosenzweig *et al* (2001).[60] Both studies conclude that agricultural yields are most likely to increase in high and mid-latitude, but decrease in tropical and subtropical developing countries, where adaptive capacity is also more limited.   A number of authors (Reilly *et al*, 1994;[61] Rosenzweig *et al,* 1993[62]) have concluded that global trade will function as a means for adapting to regional shifts in productivity, and Duchin (2005)[63] describes a model that determines the potential trade flows of such global transactions. Additional work would be required to evaluate the shifts in energy consumption associated with these shifts in global trade flows.

It is possible, however, that global trade's efficacy as an adaptive mechanism may be limited, and regions experiencing significant losses in productivity may also experience large-scale emigration as a result of diminished food security and lack of alternatives to farming as a livelihood. The issue of climate change-induced shifts in agricultural productivity as a catalyst for population migration- particularly from tropical and subtropical zones in Africa and Asia- has been discussed in a number of sources, including McGregor (1994),[64] IPCC (2001),[65] and Devereux and (2004).[66] There is relatively little literature available that discusses the implications of such migrations on regional energy demands, though in 2003, a report written for the US Department of Defense discusses potential conflicts arising, in part, from population migrations caused by an abrupt climate change event.[67]

Clearly energy demand will decline in regions depopulated by climate-induced emigration, while regions faced with an increase in immigrants will likely experience demand increases (although this will depend on whether or not the new immigrants can be assimilated without major social and economic disruptions—sudden large-scale mass migrations could result in severe economic disruption and contraction both in the origin and destination regions). Assuming a shift from less-developed tropical and sub-tropical zones to more-developed temperate zones, the global fuel and energy technology mix could likewise shift, e.g., from less-efficient supply technologies

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[59] IPCC. "Third Assessment Report- Impacts, Adaptation and Vulnerability." 2001. http://www.grida.no/climate/ipcc_tar/wg2/368.htm. Accessed 5/28/07.
[60] Rosenzweig, C., Iglesias, A. Yang, X.B., Epstein, P., Chivian, E. "Climate change and extreme weather events- Implications for food production, plant diseases, and pests." *Global Change and Human Health, Vol. S, No. 2.* 2001. Available at: http://pubs.giss.nasa.gov/docs/2001/2001_Rosenzweig_etal.pdf. Accessed 5/28/07.
[61] Reilly, J., Hohmann, N., Kane, S. "Climate Change and Agricultural Trade: Who Benefits, Who Loses?" 1994. *Global Environmental Change* 4(1).
[62] Rosenzweig, C., Parry, M., Frohberg, K., Fisher, G. "Climate Change and World Food Supply." 1993. Research Report No. 3. University of Oxford, Oxford.
[63] Duchin, F. "A World Trade Model Based on Comparative Advantage with m Regions, n Goods and k Factors". 2003. Economic Systems Research 17 (3).
[64] McGregor, J. "Climate change and involuntary migration: implications for food security." 1994. *Food Policy* 19(2).
[65] IPCC. "Third Assessment Report- Impacts, Adaptation and Vulnerability." 2001. http://www.grida.no/climate/ipcc_tar/wg2/368.htm. Accessed 5/28/07.
[66]Devereux, S. and Edwards, J. "Climate change and food security". 2004. IDS Bulletin 35. Available at: http://www.ingentaconnect.com/content/ids/idsb/2004/00000035/00000003/art00004
[67] Schwartz, P. and Randall, D. "An abrupt climate change scenario and its implications for United States National Security." 2003. Global Business Network. Available at: http://www.environmentaldefense.org/documents/3566_AbruptClimateChange.pdf Accessed 6/8/07.

(such as diesel generators) to more advanced technologies (combined cycle, nuclear, etc.). However, assuming effective assimilation of the new immigrants, overall global energy demand could rise significantly as standards of living within the immigrant population rise. Alternatively, if population migration were to lead to conflict rather than assimilation, the result could be significant declines in global economic production and energy use. Should these conflicts lead to protracted military engagements between countries, it is possible that energy consumption could increase during the engagements, although the end result of such a scenario would likely be a significant contraction in global trade, GDP and energy demand following as an effect of the conflicts.

As a significant consumer of water, there is potential for the agriculture sector to compete with power plants for available water resources. As discussed above, crop water requirements are determined by a complex interplay between precipitation levels, temperature, plant water use efficiency, and runoff rates, all of which vary by region, crop type, and irrigation method. Reilly *et al* (2000)[68] conclude that in the United States, on a national level, water demand in the agriculture sector will decline between 5-10 percent by 2030, and 30-40 percent by 2090. Changes in water demand on the part of agriculture, however, do not necessarily translate into greater availability for energy uses; although water demand from the agriculture sector is likely to be reduced in the West of the US, this demand will most likely be outstripped by growth in domestic and public use,[69] assuming that current upward trends in immigration and migration continue. It should, however, be noted that climate change could itself act to slow down or even reverse these population trends.

Another important interaction between the energy and agriculture sectors is the influence of climate change-induced shifts in energy prices and energy consumption on agricultural output. Increases in temperature and, in some areas, humidity will cause some agricultural equipment to operate less efficiently, thereby increasing fuel and electricity demand and costs. Energy-related expenses comprise a substantial component of overall expenses in agriculture, accounting for 14 percent of total farm cash expenses in 2005.[70] Expenditures on direct and indirect energy products are shown in Table 5.

[68] Reilly, J., Tubiello, F., McCarl, B., Melillo, J. "Climate change and agriculture in the United States; Chapter 13- US National assessment of the potential consequences of climate variability and change." USGCRP. 2000. Available at: http://www.usgcrp.gov/usgcrp/nacc/. Accessed 5/28/07.
[69] Reilly, J., Tubiello, F., McCarl, B., Melillo, J. "Climate change and agriculture in the United States; Chapter 13- US National assessment of the potential consequences of climate variability and change." USGCRP. 2000. Available at: http://www.usgcrp.gov/usgcrp/nacc/. Accessed 5/28/07.
[70] USDA. "Energy and Agriculture- 2007 Farm Bill Theme Paper." August 2006.

Table 5- U.S. farm expenditures on energy products, 2005

Energy source	Direct or indirect	Application	Total 2005 U.S. spending (billions) / Share of Energy expenditures (percent)
Fossil fuels- diesel, gasoline, LPG, natural gas	Direct	Planting, tilling, harvesting, drying, storage, transportation	$11.2 / 41%
Electricity	Direct	Irrigation, livestock facilities, dairy operations, other stationary production facilities	$3.4 / 12%
Fertilizers and Pesticides	Indirect	Fertilization and pest control	$12.8 / 47%

Source: USDA. "Energy and Agriculture- 2007 Farm Bill Theme Paper." August 2006.

Shifts in prices of direct and indirect energy products wrought by climate change could influence production decisions on the part of farmers. While there is very little literature studying this effect directly, there have been many studies exploring the role of energy costs on the agriculture sector. In exploring the drivers and responsiveness to drivers of energy demands in the U.S. agriculture sector, Miranowski (2005) [71] discusses how shifts in energy prices shape decisions on the part of agriculturalists. Key findings include:

- Over the short term, there is little room for behavioral changes to accommodate fluctuations in fuel prices;
- Over the longer term, the U.S. agriculture sector has proved resilient and adaptable to real changes in energy prices, and;
- While energy price fluctuations can be generally be weathered without significant disruption in output, energy supply disruptions can prove more costly, particularly during sensitive phases.

While climate change could have a major impact on energy demand in national economies that are heavily dependent on agriculture, it is unlikely that climate change-induced impacts on the agriculture sector will foment significant changes in the U.S. energy sector on a regional basis. Compared with other sectors, the agriculture sector accounts for a relatively small share of total energy consumption in the United States; agriculture accounted for 1.7 percent of the national energy consumption in 2002.[72] It is plausible that over time, agriculture-related energy loads will migrate in conjunction with geographic shifts in the location of different crop types necessitated by changes in regional temperatures and climates, but given the relatively small energy demand of the agriculture sector and the resiliency/adaptability to changes in energy demand and prices indicated in the study discussed above (Miranowski, 2005), it is unlikely that they will stimulate wholesale changes in either the supply or demand side of the energy sector.

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[71] Miranowski, J. "Energy demand and capacity to adjust in U.S. agriculture." Paper presented to the Agricultural Outlook Forum 2005. February 2005. http://www.usda.gov/oce/forum/2005%20Speeches/miranowski.pdf. Accessed 5/25/07.

[72] Duffield, J. "Office of Energy Policy and New Uses Internal Database." USDA. 2004.

Commercial and Residential Sectors

As major consumers of electricity and fossil fuels, shifts in the quantities, types and timing of energy demands on the part of commercial and residential users as a response to climate change will have important implications for the energy sector. Given that over eight percent of all energy consumed in the U.S. is used directly for space heating and cooling purposes in residential and commercial buildings,[73] changes in residential and commercial space cooling and heating requirements (particularly electricity demands) are likely to constitute a significant impact of climate change on the energy sector. Increasing temperatures may have significant effects even in regions where overall energy use declines; for example, shifts from fossil-fired heating to electric air conditioning will change the fuel and technology mix, with consequent impacts on peak loads, T&D congestion points, and fuel and electricity prices. Second order effects, including large scale human migrations in response to changing local climates over time, will also likely have ramifications for the energy sector.

Increased temperatures

Changes in temperature directly effect the residential/commercial sectors' requirements for heating and cooling. Temperature and humidity extremes, average temperatures, degree heating/cooling days and locally available energy resources all help to determine the types of heating and cooling systems deployed, as well as residential and commercial building designs and insulation requirements. Significant changes in temperatures could precipitate shifts in regional energy requirements through altered load patterns, peak demands and fuel switching, requiring accompanying changes in transmission and distribution infrastructure and capacity requirements for electricity and fossil fuels.

Establishing the elasticity of energy demand and behavioral modifications in response to temperature change is a fundamental component of understanding the ways in which the residential/commercial sector's energy requirements will change over time. These relationships, primarily over a short time frame, have been studied extensively: Quayle and Diaz (1979),[74] Warren and LeDuc (1981),[75] Downton *et al* (1988),[76] Badri (1992),[77] Lehman (1994),[78] Lam (1998),[79] Morris (1999),[80] and Pardo *et al* (2002).[81] It is important to note, as pointed out by

[73] EIA. "Annual Energy Outlook 2007 with Projections to 2030." February 2007. Available at: http://www.eia.doe.gov/oiaf/aeo/aeoref_tab.html. Accessed 10/17/07.

[74] Quayle, R. and Diaz, H. "Heating degree-day data applied to residential heating energy consumption." Journal of Applied Meteorology, Volume 19. 1979.

[75] Warren, H. and LeDuc, S. "Impact of climate on energy sector in economic analysis." Journal of Applied Meteorology, Volume 20. 1981.

[76] Downton, M., Stewart, T. et al. "Estimating historical heating and cooling needs: Per capita degree-days" Journal of Applied Meteorology, Volume 27. 1988.

[77] Badri, M. "Analysis of demand for electricity in the United States." Energy, Volume 17. 1992.

[78] Lehman, R. "Projecting monthly natural gas sales for space heating using a monthly updated model and degree-days from monthly outlooks." Journal of Applied Meteorology, Volume 33. 1994.

[79] Lam, J. "Climatic and economic influences on residential electricity consumption." Energy Conversion Management, Volume 39. 1998.

[80] Morris, M. "The impact of temperature trends on short-term energy demand." EIA. 2001.

[81] Pardo, A., Meneu, V. et al. "Temperature and seasonality influences on the Spanish electricity Load." Energy Economics, Volume 24. 2002.

Sailor (2001)[82], that energy demand responses to climate vary significantly by region, and are affected by the composition of local economies.

Most studies of climate change impacts on the U.S. predict that overall energy demand will increase, attributable primarily to increases in electricity demand for interior cooling.[83] Net energy demand is projected to increase the most in hotter climates, such as the Southwestern United States, while in cooler regions net energy increases may be small or net savings may result. Studies of space heating and cooling demand that look beyond the U.S. are limited, but based on the available analyses decreases in end-use demand are predicted for some other regions around the world. Regions that rely heavily on air conditioning will experience higher, longer peak loads. Even if this effect is offset by warmer winters, electricity supply requirements and costs will be driven upward by the increased peak demand.

At the national level, Mansur *et* al (2005)[84] developed a multinomial logit (or discrete-continuous) fuel choice model[85] of the residential and commercial sectors to determine the sensitivity of U.S. energy demand to climate change. The authors concluded that, "…warming will increase American energy expenditures, resulting in welfare damages that increase as temperatures rise. Increases in electricity expenditures for cooling are partially offset by reductions in expenditures on other fuels for heating; warming leads both firms and homes to move towards choosing only electricity to heat and cool. This fuel switch is sometimes more important than changes in the quantities of fuels chosen."[86] The switch towards electricity for heating is expected to occur because the relatively low capital costs associated with electric space heating renders it attractive given milder winters. The authors cite several other studies from the 1990s on the impact of climate change on U.S. energy demand, most of which projected similar trends. In a similar, previous study, Mansur *et al* (2004)[87] estimate the financial damages (increased energy expenditures on the part of consumers) associated with these trends on the order of $40 billion annually by 2100.[88]

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[82] Sailor,D. "Relating residential and commercial sector electricity loads to climate – evaluating state level sensitivities and vulnerabilities." Energy, Volume 26. 2001.

[83] Feenstra, J. *et al*. "UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies, Chapter 11 – Energy." UNEP/IVM. 1998.

[84] Mansur, E.T., R. Mendelsohn, and W. Morrison, "A Discrete-Continuous Choice Model of Climate Change Impacts on Energy," Social Science Research Network, Yale School of Management Working Paper No. ES-43, Yale University, New Haven, January 2, 2005, http://www.earthinstitute.columbia.edu/cgsd/documents/mansur.pdf.

[85] A multinomial logit model is used for data in which the response is often a set of choices and is therefore measured on a nominal scale.

[86] Mansur, E.T., R. Mendelsohn, and W. Morrison, "A Discrete-Continuous Choice Model of Climate Change Impacts on Energy," Social Science Research Network, Yale School of Management Working Paper No. ES-43, Yale University, New Haven, January 2, 2005, http://www.earthinstitute.columbia.edu/cgsd/documents/mansur.pdf.

[87] Mansur, E., Mendelsohn, R., Morrison, W. "A Discrete-Continuous Choice Model of Climate Change Impacts on Energy." Yale SOM Working Paper No. ES-43. March 14, 2005. Available at: http://ssrn.com/abstract=738544. Accessed 6/16/07.

[88] Mansur, E., Mendelsohn, R., Morrison, W. "A Discrete-Continuous Choice Model of Climate Change Impacts on Energy." Yale SOM Working Paper No. ES-43. March 14, 2005. Available at: http://ssrn.com/abstract=738544. Accessed 6/16/07.

In a separate study, EPRI (2003) [89] concluded that climate change would increase energy expenditures in California. Specifically, as a result of higher temperatures, both residential and commercial interior cooling demand and associated expenditures would increase, outweighing the impacts from the expected decline in residential and commercial demand for winter space heating. Southern California is expected to experience the greatest increase in energy demand, while Northern California and high-altitude locations may observe moderate increases or decreases in net energy use.

Amato *et al* (2005)[90] advocate examining the impacts of climate change on the energy sector on a more refined scale in order to capture region-specific responses; their 2005 study examines electricity and fuel demand sensitivities in the commercial and residential sectors in response to climate change in the Commonwealth of Massachusetts. They similarly conclude that climate change is likely to result in decreased winter heating and fuel use, but also in larger increases in summer electricity demands for cooling.

A 1991 study by the United Kingdom Climate Change Impacts Review Group indicated that in the generally cool climate of the United Kingdom, overall energy demand will decline because the decrease in interior heating demand more than offsets the increase in electricity demand for space cooling.[91]

On a larger scale, regional changes in temperature patterns could affect the energy sector through population shifts as residential and commercial centers migrate to regions with more favorable climates.

While the impact of climate change on space heating and cooling requirements is likely to have by far the largest global indirect impact on the energy sector, other climate-related changes, such as increased incidence of extreme storms, sea-level rise, and precipitation changes may prove as significant, and even more significant, for some regions and localities. In the remaining subsections below these other potential effects are briefly considered.

Increased incidence of extreme weather events

Increased frequency of extreme weather events can be expected to lead to greater risk of damage for residential and commercial buildings. Should building damage increase significantly, financial and energy inputs associated with rehabilitation and reconstruction could also be expected to increase. As discussed by Mills,[92] as the costs of damages from extreme weather

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[89] Electric Power Research Institute. "Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy," Prepared for the California Energy Commission, Public Interest Research Program, 500-03-058CF. August 2003. Available at: http://www.energy.ca.gov/pier/final_project_reports/500-03-058cf.html.

[90] Amato, A., Ruth, M., Kirshen, P. and Horwitz, J. "Regional Energy Demand Responses to Climate Change: Methodology and Application to the Commonwealth of Massachusetts." *Climatic Change*, Vol. 71, No. 1, July 2005. Available at: http://www.puaf.umd.edu/faculty/ruth/Papers/regional_energy.pdf. Accessed 6/15/07.

[91] Jan F. Feenstra *et al*., *UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, Chapter 11 – Energy, Frank Stern, UNEP/IVM, 1998.

[92] Mills, E. "Insurance in a climate of change." *Science*, Vol 309. 8/12/05. Available at: http://www.sciencemag.org/cgi/reprint/309/5737/1040.pdf. Accessed 10/15/07.

events continue to grow and impact virtually all sectors of the economy, the ability to obtain suitable catastrophic insurance coverage may become an increasingly important factor in business and homeowner's decision-making process. Over time, this factor may contribute to population shifts, with populations moving away from areas with a greater vulnerability to extreme weather events.

Sea level rise

Rising sea levels can also contribute to population shifts as susceptible coastal areas become less habitable due to inundation and salinization of groundwater resources. Any major population shifts caused by climate change can be expected to have effects on regional power demands and requirements. While there is substantial literature that qualitatively describe potential impacts on human migrations,[93] far less work has been done to quantitatively assess these shifts, much less their implications for the energy sector.

Changes to hydrologic cycle/water availability

Changes in temperature, evaporation and precipitation patterns will change the hydrologic cycle of a given area, influencing water resources and availability. In some regions climate change may exacerbate water supply problems that are being caused by non-climate related factors. In areas experiencing declining water availability, it can be expected that there will be increased competition between the agriculture, power, industrial, and commercial/residential sectors for water resources. Decreased water availability and increases in costs and pumping requirements all stand to affect both the power and commercial/residential sectors.

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[93] For a comprehensive overview of the potential impacts of climate change on human populations, see: IPCC. "Third Assessment Report- Impacts, Adaptation and Vulnerability, Chapter 7- Human Settlements and Industry." 2001. http://www.grida.no/climate/ipcc_tar/wg2/368.htm. Accessed 5/28/07.

Industrial Sector

The industrial sector is susceptible to the risks of climate change and many of these risks have the potential to indirectly affect the energy sector in a significant way. Major industries that will be affected by climate change include manufacturing, construction, tourism and recreation, agro-industries, textiles, steel, cement, aluminum, mining, fishing and forestry. Some of the consequences of climate change that could impact industry include changes in temperature, changes in precipitation amounts and water resources, changes in the intensity and pattern of extreme weather events, and flooding and/or sea level rise. Many of the direct impacts of climate change on the industrial sector will have indirect impacts on the energy sector including changes in energy demand, competition for water resources, and changes in critical energy infrastructure investment decisions. Furthermore, concerns about these consequences have the potential to influence energy policies as well as change the perceptions, valuations, demonstration, and development of energy technology alternatives. The following is a summary of some of these issues.

Fluctuations in temperature

An increase in temperature may have a number of potential impacts on the industrial sector. Higher temperatures may, in some regions lead to changes in energy used for space heating and cooling of industrial facilities and associated offices, plants, etc. Higher temperatures may also lead to changes in the amount of energy required for industrial temperature-controlled processes and storage refrigeration needs. However, these effects are likely to prove minor; in the United States process cooling and refrigeration accounts for only 2 percent of the total energy used by manufacturing industries, while space heating and cooling accounts for an additional 4 percent.[94]

For certain industries (e.g. skiing/tourism) increased temperatures may prove devastating. For example, ski resorts could be severely impacted by shorter snow seasons and an increase in the need for snow making machines, although at the same time warm weather resorts (e.g., golf resorts and clubs) could see an expansion of their operating season, leading to a shift in regional energy consumption patterns associated with the tourism industry. However, it must be emphasized that the major energy-intensive industries (e.g., steel, chemicals, cement, aluminum, paper) appear much less sensitive to direct temperature change impacts. Nonetheless, demand for the products produced by these industries may be affected by warming trends. For example, to the extent that higher temperature extremes cause expansion-related cracking and buckling of concrete infrastructure (roads, bridges, etc.), demand for cement, asphalt, other associated building materials and the energy needed to produce them might also increase. On the other hand, reduced precipitation in the form of snow and ice might lead to a reduction in infrastructure damage during winter months, which could well offset the impact of heat-related damage. Similarly, temperature-related changes in agriculture may impact demand for fertilizers and pesticides, although it is very difficult to project the direction, let alone the magnitude, these potential demand changes may take. To the extent that climate change leads to an overall decline in global GDP (as projected, e.g., in the “Stern Review on the Economics of Climate

[94] EIA, 2002 Manufacturing Energy Consumption Survey.

Change,"[95]) one would expect industrial production as a whole to decline, along with industrial energy use.

Changes in precipitation amounts, seasonal patterns, and water resources

Climate change has the potential to significantly alter precipitation amounts and seasonal patterns in many different regions.[96] In certain areas, decreased runoff from rain, snow, sleet, or hail will lead to an overall decrease in surface and groundwater supplies. This may directly impact industrial facilities that use water for cooling processes, potentially forcing them to invest in increased storage capacity and water pumping facilities to maintain existing water supplies. Energy demand to meet increased water pumping requirements may be affected in some cases. In addition, in areas where environmental waste-heat discharge compliance laws are in effect, additional energy will be needed to cool discharge water.[97] Water shortages may lead to increased competition between power plants and other industrial users for constrained supplies. According to the U.S. Global Change Research Program, "climate change will very likely exacerbate competition in regions where fresh water availability is reduced by increased evaporation due to increases in temperature…"[98] A reduction in surface water supplies could lead to increased reliance on groundwater sources, which often need to be treated for certain industrial applications. For aesthetic, health, and process reasons, groundwater used for industrial processes is often treated to remove organic compounds. This allows the water to be discharged to the environment and mixed with surface water. Industrial companies such as chemical manufacturers may need to utilize more energy intensive water treatment technologies (e.g. ultraviolet light treatment technology[99]).

Decreased precipitation may lead to a drop in reservoir water levels and hydroelectricity generation.[100] Electricity shortages in areas dependent upon hydropower may negatively impact industries that are highly dependent on constant electricity supplies. Furthermore, to the extent that decreased precipitation is a long-term phenomenon, it may become necessary to replace hydropower capacity with higher-cost electricity sources. The impact on industries that rely heavily on low-cost electricity—most notably the aluminum industry—could prove severe. Reduced hydropower generation in some regions could lead to geographic shifts in the

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[95] Stern *et al*. "Stern Review: The Economics of Climate Change." HM Treasury, UK. 10/30/06. Available at: http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm. Accessed 10/15/07.

[96] MacCracken, Michael C., *National Assessment of the Consequences of Climate Variability and Change for the United States*, discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/maccracken.pdf

[97] It is possible that these laws could be revised if climate change raises normal water temperatures.

[98] U.S. Global Change Research Program, U.S. National Assessment of the Potential Consequences of Climate Variability and Change, Water Sector Overview, Pg. 3, Available: http://www.usgcrp.gov/usgcrp/Library/nationalassessment/16WA.pdf

[99] Vere, Henry, "UV Light", in Onsite Water Treatment: The Journal for Decentralized Wastewater Treatment Solutions, March / April 2007, Available: http://www.gradingandexcavation.com/ow_0703_uv.html

[100] Gleick, Peter H., *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States*, Report of the Water Sector Assessment Team of the U.S. National Assessment of the Potential Consequences of Climate Variability and Change for the U.S. Global Change Research Program, Available: http://www.gcrio.org/NationalAssessment/water/water.pdf

production of aluminum and other energy-intensive commodities, and/or increases in commodity prices with negative macroeconomic implications.

While some regions are expected to experience declines in precipitation due to climate change, others may face increased risks of flooding. The mining industry is particularly vulnerable to flooding risks. Mining processes and operations contain pits, drainage systems, tailings, and mineral waste disposal facilities. Flooding can significantly increase environmental compliance costs and general expenses to maintain and update facilities accordingly. Electricity demand for pumping out flooded areas of mines may also be affected.

Changes in the intensity and pattern of extreme weather events

Climate change may lead to an increase in the frequency and intensity of extreme weather events such as hurricanes and tornados.[101] Weather related natural disasters and extreme weather events have the capacity to damage industrial structures such as manufacturing plants. Increased construction activity to repair damages may provide short term benefits for the construction industry, but for others this will cause losses of income and property, increase companies' insurance costs, and yield a net reduction in GDP. The supply disruptions, property losses and insurance costs may in turn be passed on to consumers in the form of higher commodity prices, with potential implications for trade patterns (reduced production in hurricane-prone areas), overall economic growth, and both regional and global energy demand. Agro-industries that are heavily reliant on the production and transport of products like grain, sugar, and rubber are particularly vulnerable to changes in the frequency and intensity of extreme weather events.[102] To the extent that industry chooses to remain in hurricane-prone areas rather than migrate, the need to repair damaged plants may lead to increased demand for energy-intensive building materials such as cement and steel.

Sea level rise and flooding

Sea level rise may force the relocation of industrial facilities, or the construction of seawalls to protect these facilities. Furthermore, in coastal and low-lying areas, underground water aquifers are susceptible to increased saltwater concentrations as sea level rises. Hence the need for water treatment may increase, along with demand for energy used in the treatment process.

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[101] MacCracken, Michael C., *National Assessment of the Consequences of Climate Variability and Change for the United States*, discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/maccracken.pdf

[102] Intergovernmental Panel on Climate Change, *The Regional Impacts of Climate Change An Assessment of Vulnerability*, Chapter 6 Latin America, Section 6.3.7 Industry, Energy, and Transportation, Available: http://www.grida.no/climate/ipcc/regional/147.htm

Transportation Sector

Fluctuations in temperature

Higher temperatures may have a number of impacts on the transportation sector that could, in turn, indirectly affect the energy sector. As the maximum efficiency of internal combustion engines is limited in part by the difference between their hottest and coldest operating cycles, the efficiency of all internal combustion engine-propelled vehicles will decline slightly as ambient temperatures increase. In addition, cars, trucks, buses and locomotives are likely to use more fuel due to greater air conditioning use and refrigeration needs. It is estimated that the average automobile in the United States uses 20 gallons of gasoline to run its air conditioner for every 10,000 miles driven. .[103] Offsetting this effect to some extent, there may be a decrease in fuel demand due to the reduced use of high-resistance snow tires and defrosting systems.[104] In order to accommodate higher road and air temperatures, tire compound formulations may be changed over time. Furthermore, drivers may adjust their driving patterns such that the summer driving season either becomes longer or shifts into different months. Although it is impossible to positively predict the effect of climate change on transportation demand patterns, it does seem that whatever changes occur will have an impact on energy prices and fuel availability.

Higher temperatures may result in an increase in asphalt "rutting" and buckling of transportation infrastructure (e.g. railroad tracks, bridges, etc.).[105] This can have the impact of increasing the demand for energy to produce cement, steel, asphalt, and other construction materials needed to replace damaged infrastructure. The increased occurrence of damage to railroad tracks from excessive heat may cause short-term disruptions to the flow of key energy supplies (e.g. coal and ethanol). In July 2002, an Amtrak train accident in Maryland may have been caused by the buckling of the tracks due to extreme heat.[106] For airplanes, higher temperatures will generally lead to reduced cargo carrying capacities. This follows from the fact that air density is inversely proportional to air temperature, and air density reductions will in return reduce lift at set speeds.[107] The overall impact will be an increase in fuel consumed per ton of cargo transported by air. However, to the extent that this impact leads to an increase in prices for air transport, shipping demand may shift from air towards less energy-intensive rail and barge transportation.

[103] Titus, J.G. (1992) "The costs of climate change to the United States," in S.K. Majumdar, L.S. Kalkstein, B. Yarnal, E.W. Miller and L.M. Rosenfeld (eds.), (1991), Global Climate Change: Implications, Challenges and Mitigation Measures, Easton: The Pennsylvania Academy of Science, 385-409. http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BWHXY/$File/us_costs.pdf

[104] Natural Resources Canada, Earth Sciences Sector, "Climate Change Impacts and Adaptation: A Canadian Perspective – Impacts on Transportation Operations" Website, Available: http://adaptation.nrcan.gc.ca/perspective/transport_4_e.php

[105] Natural Resources Canada, Earth Sciences Sector, "Climate Change Impacts and Adaptation: A Canadian Perspective – Impacts on Transportation Infrastructure" Website, Available: http://adaptation.nrcan.gc.ca/perspective/transport_3_e.php

[106] CNN, "Six critically injured in train derailment", July 30, 2002. http://archives.cnn.com/2002/US/07/29/amtrak.derailment/

[107] Natural Resources Canada, Earth Sciences Sector, "Climate Change Impacts and Adaptation: A Canadian Perspective – Impacts on Transportation Operations" Website, Available: http://adaptation.nrcan.gc.ca/perspective/transport_4_e.php

In Arctic regions such as Alaska, transportation infrastructure located on permafrost will be subject to twisting and displacement due to subsidence.[108] If Hudson Bay's navigation season is significantly extended as a result of climate change, Canada could become a primary import/export point for the U.S.[109] In particular, the Port of Churchill in Manitoba, Canada could become a major import point for energy supplies to the United States.[110]

Changes in precipitation amounts and seasonal patterns

Climate change has the potential to significantly alter precipitation amounts and seasonal patterns in different regions.**[111]** Increased rain, snow, sleet, or hail could lead to an increase in traffic congestion, road maintenance requirements, and damage to vehicles both from increased accident rates and the effects of road salt. Heavy amounts of rain also have the potential to increase the frequency and risk of floods and landslides that can destroy roads and critical transportation infrastructure.**[112]** In areas where climate change causes reduced precipitation and falling water levels, inland shipping operations and systems may be severely impacted. It may, for example, become necessary to widen or deepen locks, dredge appropriate shipping lanes, and invest in vessels or ships with less draft. Given that much of the nation's coal is moved by barge, delivered coal prices may increase, either due to higher barge shipment costs or an increased reliance on more expensive forms of transportation (rail and truck).**[113]**

Changes in the intensity and pattern of extreme weather events

Climate change may lead to an increase in the frequency and intensity of extreme weather events such as hurricanes and tornados.[114] These extreme events can pose major problems for transportation systems and infrastructure in areas prone to extreme storms. Damage to critical transportation infrastructure (e.g. energy transportation infrastructure in the Gulf of Mexico[115]) can impact the flow of critical energy supplies throughout the nation, thus impacting energy prices and leading to increased market volatility.

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[108] Smith, Orson P., and Levasseur, George, "Impacts of Climate Change on Transportation Infrastructure in Alaska", discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/smith.pdf

[109] Kraus, et al., "As Polar Ice Turns to Water, Dreams of Treasure Abound", *The New York Times*, Monday, October 10, 2005, Available: http://www.broe.com/news27.html

[110] Ibid.

[111] MacCracken, Michael C., *National Assessment of the Consequences of Climate Variability and Change for the United States*, discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/maccracken.pdf

[112] United Nations University, "Climate Change will mean more landslides, experts warn", The Newsletter of the United Nations University, Issue 40, November 2005-February 2006 http://update.unu.edu/archive/issue40_10.htm

[113] Quinn, Frank H., *The Potential Impacts of Climate Change on Great Lakes Transportation*, discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/quinn.pdf

[114] MacCracken, Michael C., *National Assessment of the Consequences of Climate Variability and Change for the United States*, discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/maccracken.pdf

[115] Burkette, Virginia R., *Potential Impacts of Climate Change and Variability on Transportation in the Gulf Coast / Mississippi Delta Region*, discussion paper presented at a Department of Transportation workshop held October 1-2, 2002 at the Brookings Institution, Washington, D.C. http://climate.volpe.dot.gov/workshop1002/burkett.pdf

Sea level rise and flooding

Sea level rise may have potentially significant impacts on transportation infrastructure and, indirectly, the energy sector. Areas that are hit hardest may need to relocate roads, highways, bridges, ports, inland waterways and other important transportation infrastructure.[116] If sufficient land area is lacking for relocation, the result may be an increase in traffic congestion and fuel consumption. Furthermore, the relocation of transportation infrastructure may in turn impact energy infrastructure siting decisions.

[116] Natural Resources Canada, Earth Sciences Sector, "Climate Change Impacts and Adaptation: A Canadian Perspective – Impacts on Transportation Infrastructure" Website, Available: http://adaptation.nrcan.gc.ca/perspective/transport_3_e.php

IV. NETL Activities Likely to Improve the Energy Sector's Ability to Adapt to Climate Change

Previous chapters of this paper discuss the potential ways in which climate change may impact the energy sector, both directly and indirectly. The purpose of this chapter is to explore NETL-funded activities that are likely to increase the energy sector's ability to adapt to those changes, and, where applicable, the impact of climate change itself on those activities. In some cases, increased energy sector resilience or adaptability to climate change is a secondary benefit of a program designed to achieve another, more direct goal. In other cases, a single impact of climate change may be indirectly addressed by more than one activity area.

A list of the ways in which climate change is likely to directly affect the energy sector is provided on page 3; this chapter is divided into discussions of key NETL activity areas and programs that may influence some aspects of the energy sector's ability to adapt to those effects.

Innovations for Existing Plants

NETL's Innovations for Existing Plants (IEP) program is focused on maximizing the environmental performance of the nation's coal-fired power generators through innovative research, development and demonstration (RD&D) programs. Recognizing the fundamental interdependence between the energy sector and water resources, many of the initiatives under the IEP seek to generate solutions to challenges arising from water scarcity through innovative technologies and water management practices. These water-related initiatives are focused on either reducing the water-use intensity of thermal power generating practices, or identifying alternative sources of water that might be unsuitable for use in other sectors, but could be used to meet the needs of thermal generators. Improvements in the ability of power plants to reduce their demand for conventional freshwater resources will better enable them to adapt to an environment in which climate change exacerbates competition for increasingly scarce water supplies. Key research areas of the IEP initiative that will help meet these goals are listed below.

<u>Water re-use and recovery</u>

- *Desiccant-enabled water extraction from coal-fired power plant flue gas*
- *Water recovery from boiler flue gases at coal-fired power plants through condensing heat exchangers, allowing plants to recover from 25-37% of a plant's cooling tower make-up water requirements*
- *Reduction of cooling tower water evaporation through coal drying with waste heat—prior to entering the cooling towers, hot water from the condenser is used to evaporate moisture from the coal. Cooler water in the cooling towers reduces the quantity of water (and associated evaporation) required to bring it to condensing temperature, while drier coal improves efficiency and reduces emissions from the plant. Coal test burns and theoretical analyses by NETL show decreases in cooling tower makeup requirements in a 572 MW coal-fired plant of 140 to 380 gallons per minute, depending on the cooling system employed.*

- *Reduction of evaporative water loss in FGD systems through the use of regenerative heat exchangers, which can reduce FGD water consumption by up to 50 percent*

Non-traditional waters

- *Offsetting raw water use in recirculating cooling systems with produced water from oil and gas fields—at a current test site, produced water may be able to meet up to 25 percent of the cooling water requirements of a 1800 MW coal-fired plant*
- *Offsetting raw water use in coal-fired power plant cooling processes with cool water from coal mine discharges—NETL-funded studies identified four mines in the Pittsburgh coal basin with sufficient water resources to cost-effectively provide cooling water for a 600 MW coal-fired power plant*
- *Offsetting raw water use in coal-fired power plant cooling processes with three types of impaired waters- secondary treated municipal wastewater, passively treated coal mine drainage, and ash pond effluent*
- *Production of fresh water through desalinization using power plant waste heat*
- *Development of physical and chemical technologies to minimize pipe scaling by impaired waters, enabling greater use of alternative water sources for cooling systems while minimizing waste discharge*
- *NETL's in-house R&D department is developing novel approaches for the remote sensing and mapping of underground water resources that might provide alternative sources of water for power plants, including saline and impaired waters*

Advanced cooling technologies

- *Use of ice to cool air as it passes through the gas turbine air inlet- this practice not only improves plant performance in sub-optimal conditions (computer simulations show net power output gains and heat rate reductions of up to 40 and 7 percent, respectively)*[117]*, but provides an opportunity for water recovery as moisture from the inlet air condenses as it passes through the cooling system and is collected*
- *Recovery of evaporative loss from cooling towers using condensing equipment capable of recovering up to 20 percent of normal evaporative losses*
- *Development of high thermal conductivity foam to enhance the performance of air-cooled steam condensers*
- *Use of pulsed electrical fields to reduce scaling in cooling systems, allowing them to operate at maximum capacity, minimizing water requirements for cooling tower blowdown operations*

[117] These improvements are particularly beneficial during high temperature summer months when heat-induced reductions in power plant output compromise the ability of generators to meet peak demands.

Gasification Technologies Program

In addition to the goals outlined in the discussion of the IEP, above, the further development and market maturation of integrated gasification combined cycle (IGCC) power plants is an area with potential to significantly impact the power sector's demand for freshwater for cooling. IGCC is an innovative energy conversion system that "integrates" a *gasification process* with *gas turbine and steam* power generation technologies that operate in tandem as a combined power cycle. The gasification process converts coal (and other carbon-based feedstock) into a clean, combustible syngas to fuel the combined cycle. IGCC plants are typically characterized by high efficiency, low pollutant emissions and increased ease of carbon capture relative to conventional, pulverized coal plants. In 2005, NETL published a study that examined patterns of water usage at seven conceptual fossil fuel-fired power plants, including four commercially available IGCC plant configurations employing different gasification systems:[118]

-ConocoPhillips E-Gas IGCC (E-Gas), 526 MWe, 39.2% efficiency (HHV)

-Shell IGCC (Shell), 537 MWe, 40.1% efficiency (HHV)

-GE Radiant-Connective IGCC (GE R-C), 571 MWe, 39.4% efficiency (HHV)

-GE Energy Quench IGCC (GE Quench), 522 MWe, 35.4% efficiency (HHV)

-GE 7FA Natural Gas Combined Cycle (NGCC), 534 MWe, 49.9 efficiency (HHV)

-Generic Subcritical Pulverized Coal (PC Sub), 521 MWe, 35.4 efficiency (HHV)

-Generic Supercritical Pulverized Coal (PC Super), 518 MWe, 39.9 efficiency (HHV)

The results of the findings are summarized in Table 6.

Table 6- Summary of water losses and raw water usage for various fossil plants

Plant	E-Gas	Shell	GE R-C	GE Quench	NGCC	PC Sub	PC Super
Water Losses (gallons/MWh)							
Process Losses	26	25	29	34	0	9	8
Flue Gas Losses	106	77	78	105	87	107	95
Cooling Water Losses	608	695	707	762	497	1104	984
Total	**739**	**797**	**814**	**901**	**584**	**1,220**	**1,087**
Raw Water Usage (gallons/MWh)							
Makeup to Cooling	606.7	694.1	701.7	737.6	494.9	1099	979.8

[118] NETL. "Power plant water usage and loss study." August 2005. Available at: http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/pdf/WaterReport_IGCC_Final_August2005.pdf Accessed 7/18/07.

Plant	E-Gas	Shell	GE R-C	GE Quench	NGCC	PC Sub	PC Super
Tower							
Other Uses	71.5	50.3	48.5	85.5	1.9	70	62.2
Total	**678.2**	**744.4**	**750.2**	**823.1**	**496.9**	**1,169**	**1,042**

Table 6 shows the variation in overall water requirements between different fossil fuel-fired thermal power plants. "Water Losses" represent the total quantity of water lost from the plant to the environment, and includes water that originally enters the plant through humidity in intake air, moisture contained in fuels, and water that is generated as a byproduct of combustion or gasification. Many of these sources are not reflected in the "Total Raw Water Usage," which represents the total quantity of water delivered to the plant, and is an important figure for evaluating a plant's potential impact on local water resources during the siting process. As indicated in the table, cooling water losses (including losses from cooling tower blowdown and evaporation) account for most of the total quantity of water lost from most fossil-fired thermal power plants. Similarly, the vast majority of raw water usage is intended for cooling processes, as indicated by the quantity used for "Makeup to Cooling Tower."

Table 6 shows that water demand requirements for IGCC plants range between 58 and 79 percent of those for comparably sized PC plants. This large difference is highly relevant to the U.S. power sector. In 2006, approximately 51 percent of the electricity generated in the United States was generated by coal-fired plants,[119] 99 percent of which are PC plants.[120] Coal-fired generation's share of net generation is expected to continue to grow, reaching 57% by 2030.[121] Considering the scale of the difference, and the magnitude of freshwater withdrawals associated with coal-fired power plants in the US, greater adoption of IGCC plants could significantly reduce water requirements for coal-fired power generators on a national scale.

Carbon Capture and Storage

Another area of NETL R&D that relates to IGCC plant development is carbon capture and storage (CCS), a subsection of research in the field of carbon sequestration. As implied by its name, capture and storage entails two main activities—the separation and collection of carbon dioxide from the atmosphere or an emission stream, and its subsequent long-term placement in a geologic formation. Typical formations include depleted oil/gas reservoirs, unmineable coal seams, and underground saline aquifers.

While carbon capture can theoretically be applied to any carbon dioxide containing emission stream, IGCC plants have a number of attributes that lend themselves particularly well to it. Gasification processes that operate at elevated pressure and use high-purity oxygen can be configured to yield syngas, which is composed primarily of hydrogen (H_2) and carbon dioxide

[119] EIA. "Annual Energy Outlook 2007. Electricity- Supply and demand." 2007. http://www.eia.doe.gov/oiaf/forecasting.html. Accessed 6/19/07.
[120] "Carbon Sequestration- CO2 Capture." NETL website. http://www.netl.doe.gov/technologies/carbon_seq/core_rd/co2capture.html. Accessed 6/17/07.
[121] Zwaniecki, A. "United States advances $1 billion for clean coal projects." November, 2006. USINFO. Available at: http://usinfo.state.gov/xarchives/display.html?p=washfile-english&y=2006&m=November&x=20061130172755SAikceinawz0.3671076 . Accessed 6/18/07.

(CO_2). These constituents can be separated using commercial or advanced capture equipment, which yields hydrogen gas and a pure stream of CO_2 that can be readily captured for sequestration purposes. Oxygen combustion is another approach to capturing CO_2 from coal plants, and relies on combusting coal in an oxygen-rich environment. This results in a flue gas of pure oxygen and CO_2, from which the CO_2 is extracted by condensing the water. An added benefit of this method is that the condensed water can be reclaimed to offset demand for external water supplies for power plant operations.

Adding a capture and storage component to any plant will add to the complexity and cost of that plant. In addition, some of the steps of the CO_2 capture process are energy intensive, and will detract from overall plant efficiency and output; energy intensive processes include compressing CO_2, producing syngas, and steam extraction from the steam turbine in the case of non-quenched gasifiers. However, it is worth noting IGCC plants fare better than other plants in terms of overall efficiency reductions associated with carbon capture. IGCC plants can be expected to experience efficiency reductions of about 15 percent, compared with 25 percent for natural gas combined cycle plants, and 38 percent for supercritical PC plants.[122]

Carbon capture and storage represents a significant opportunity for the U.S. power sector to *mitigate* its impact on climate change. Furthermore, because applications of CCS to the power sector are likely to prove commercially feasible only, or at least primarily, when combined with IGCC, the resulting hybrid technology may improve prospects for *adapting* to climate change. As discussed previously, coal is likely to retain a dominant role in the U.S. power sector, and the commercial development of CCS is a critical step in adapting IGCC to a carbon-constrained economy. By the same token, IGCC may prove important as a means of adapting CCS to a water-constrained environment. Thus the technical and economic synergies between IGCC and CCS that are already well known may have an important parallel in their environmental characteristics. Few if any other fossil technologies combine the carbon reduction potential with the water demand reduction potential of IGCC with CCS. In addition to its IGCC R&D efforts, NETL funds innovative R & D efforts focused on 1) lowering the financial and energy costs associated with CO2 capture, and 2) furthering knowledge of CO2 storage permanence, capacity and long term safety in geologic formations. Additionally, NETL manages seven regional carbon sequestration partnerships that engage state agencies, universities, and private companies in determining the most suitable technologies, regulations, and infrastructure needs for carbon capture, storage, and sequestration.

Modern Grid Initiative

Significant power failures in North America in recent years, including the western blackouts of 1996, the Western power crisis of 2000, the Northeastern blackout of 2003, and the T/D infrastructure failure-induced blackouts in Southern California and in Queens, NY during the summer of 2006 have brought increased attention to the vulnerability of the grid to disturbances, and the potential for small problems to escalate rapidly into major disruptions. Given the likelihood that climate change will increase the frequency of extreme weather events that have

[122] Ratafia-Brown, J. "Integrated gasification combined cycle (IGCC) & CO2 capture and storage (CCS) – Background and Technical Issues." Written for EPA. 6/5/06.

the potential to damage critical grid infrastructure and cause similar failures, many of the efforts intended to increase the resiliency of the grid will also increase its capacity to adapt to extreme weather events.

NETL's Modern Grid Initiative (MGI) is a DOE-sponsored effort to identify, plan for and implement a wide-scale modernization of the nation's aging power grid system with state-of-the art technologies through 2030. Through the MGI, the power grid will benefit from increased transmission efficiency, greater reliability, resiliency, and greater adaptability to other changes throughout the power sector. The existing grid system is based on a highly centralized generation scheme, with a consequent heavy reliance on transmission and distribution infrastructure to serve the widely dispersed loads. The modernized grid, in contrast, will accommodate a more decentralized plan that utilizes more distributed generating resources, a more diverse array of power generators, and technologically advanced power transmission and distribution systems. As a result of this modernization process, the NETL outlines seven key beneficial characteristics of the modern grid:

- *Self healing*- increasingly, the grid will be able to automatically detect and respond to existing and imminent problems on the grid system with minimal human intervention.
- *Greater customer involvement*- through real time pricing incentives and "intelligent load" end use devices responsive to signals from the grid.
- *Resistant to attack*- the modernized grid will be able to withstand significant physical and computer-based attacks without compromising widespread grid stability
- *Improved power quality*- improved power generation, storage, transmission and distribution systems will increase reliability while decreasing outages, voltage spikes, and other costly aberrations in power supply.
- *Ability to accommodate a wider range of generator types*- as smaller scale power generating technologies mature, the grid will need to be able to interconnect with power sources in non-conventional sites (i.e. commercial and residential sites) and accommodate a growing flow of two-way power transfers between the grid and consumer/producers.
- *Facilitates more efficient free market operation*- through improved transmission and pricing mechanisms that enable more responsive planning and purchasing options.
- *Increased operational efficiency*- improved monitoring and information communication will allow disparate components of the grid to be utilized collectively in the most cost effective combination.

Although they may be intended primarily to serve other purposes, a number of the technological and infrastructural advancements encompassed by the MGI program also serve to decrease the likelihood of weather-induced damages to the grid, and by limiting the potential of such failures to escalate into larger problems.

One of the goals of the MGI is to reduce the grid's vulnerability to terrorist attacks, which are categorized as either *cyber* attacks- those initiated through computer systems, or *physical* attacks- explosive or other material-based attacks directed at specific grid components. Functionally, weather-induced damages are likely to affect the grid's functionality and operability in much the same way as physical attacks to the grid. Similarly, innovations intended to reduce the grid's vulnerability to physical attacks and increase its ability to recover from them will also reduce the likelihood and severity of weather-induced damages. Elements of the Modern Grid that will increase resiliency to such damages include the following:

- Integrated communications: real time systems control will allow grid operators to respond to weather-induced damages more quickly
- Sensing and measurement: remote monitoring will detect problems on the grid immediately as they arise
- Advanced control methods: increased ability to isolate areas of the grid that have been damaged, limiting effects on neighboring areas.

The development of high-temperature superconductive (HTS) power cables is another area through which modernized grids might become more resilient to extreme weather events. Relative to conventional copper power cables, HTS cables hold promise both in their ability to conduct extremely high loads (up to 5 times the amount of conventional cables),[123] significantly reduce transmission losses, and eliminate electromagnetic fields outside of the cable. These characteristics make them well-suited for underground burial to deliver power to congested urban areas, which renders them less vulnerable to weather-related stresses including high-temperature sagging.

Modern grids will be able to efficiently and seamlessly integrate and distribute power from a wide variety of distributed energy resources, including small scale generators and power storage devices, enabling the transfer of a large share of the power sector's generating capacity to non-traditional hosts, including commercial and residential sites. Technological advancements in small scale power generators, improved interconnection standards, and the capability to remotely dispatch distributed energy resources will facilitate the development of a more decentralized grid. There are a number of reasons that a decentralized power system utilizing a larger share of distributed energy resources (DERs) is likely to be more resilient to extreme weather events than a centralized one:

- By locating power resources closer to end-users, distributed generators reduce reliance on vulnerable grid components
- Dispatchable distributed generators and power storage devices can free up T/D capacity during peak demands, reducing the incidence of equipment failure and line sagging from high temperatures and heavy loads
- Distribution of generators increases likelihood that critical loads will be close to an accessible power source

[123] Moscovic, J. "Superconducting cable connects the grid." March, 2007. Transmission and Distribution World. Available at: http://tdworld.com/underground_transmission_distribution/power_superconducting_cable_connects/ Accessed 6/18/07.

- The modular nature of the system allows small "islands" of power to exist in the face of wider scale grid disruptions; it also allows aberrations to be confined to such "islands"
- Decentralized systems are likely to incorporate a wide variety of generator types—in the event of a disruption to the supply of one energy source, other options exist.

However, these benefits can only exist in a grid system that is specifically designed to accommodate them. Developing this system is one of the overarching goals of the MGI.

In addition to HTS cables, the MGI program will help usher in advances in other power cable technologies that will increase the efficiency of transmission through overhead lines while reducing the tendency for cables to sag in higher temperatures and loads. An example of such technologies include ceramic core conductor cables recently marketed commercially by the 3M Corporation that can carry 1.5 to 3 times the power of conventional cables with much reduced sag, even at significantly higher temperatures,[124] offsetting the threat of increased line sag and associated grounding in a warmer environment.

Oil and Natural Gas Program

A number of NETL's activities in its Oil and Natural Gas program will help the oil and natural gas sectors adapt to the impacts of climate change. Relevant research areas are highlighted below.

Produced Water Treatment

Significant quantities of water are brought to the surface during oil and gas production. Most of this water is brackish and is currently pumped back into the formation or is otherwise disposed of. NETL is developing technologies to treat this water and make it suitable for human use or consumption. Projects already underway have demonstrated the ability to treat produced water so that it is suitable for agricultural and industrial uses. This ability to turn a waste stream into a valuable commodity, allows conventional water sources to be used for human consumption. As water and climate regimes change, treated produced water could become critical for many communities.

Tundra Travel Model for the North Slope of Alaska

As discussed previously, higher summer temperatures and shortened winter seasons have significantly reduced the time available per year for overland tundra travel, exploration and production activities in Alaska's North Slope. Given the economic dependence of North Slope activities on the total number of days available for exploration and drilling activities, the Alaskan Department of Natural Resources (DNR) is interested in replacing the existing, arbitrarily-set guidelines for tundra travel with ones that better reflect actual conditions. The goal of NETL's Alaska Tundra Model project is to provide this information through advanced sampling, testing and modeling activities that utilize the best available information on soil conditions, ecological

[124] "More Power to the Grid." Oak Ridge National Laboratory Review. 2005. Available at: http://www.ornl.gov/info/ornlreview/v38_1_05/article11.shtml. Accessed 6/18/07.

sensitivity, and transportation methods. Through this effort, NETL and DNR can expect to increase the exploration season while ensuring continued protection of the sensitive Alaskan tundra.

Methane Hydrates Research Program

Methane hydrates represent a massive potential domestic source of clean burning methane. Successful commercial development of producing methane from hydrates could help the United States' power sector shift to a more distributed framework by providing an abundant domestic source of a clean burning fossil fuel to fuel emerging, high-efficiency, smaller-scale distributed generating units, most of which burn (or, in the case of fuel cells, reform) natural gas. The ability to tap this resource, however, is dependent on significant advances in understanding of hydrate behavior in its natural environment, the mechanics of hydrate reservoirs, their impact on sea floor stability and the global carbon cycle, and the technological advances required to enable their detection, characterization and commercial extraction. NETL's Hydrates research program is centered on overcoming these barriers through extensive R&D programs, focused on addressing all of these developmental needs and is driven by the goal of achieving commercial production of hydrates by 2015.

Energy Infrastructure Analysis Group

Increased incidence of extreme meteorological events is likely to increase the frequency of weather-induced damages to important energy sector infrastructure. As a producer of high-level analytical visualizations of critical energy infrastructure, the interactions between them and their vulnerability to incoming threats, NETL's Energy Infrastructure Analysis Group is an important contributor to the Nation's emergency preparedness and response activities. NETL coordinates these activities with efforts from a host of other research labs, including Argonne National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories to provide DOE's Office of Electricity Delivery and Energy Reliability and the Department of Homeland security with a common operational picture to quickly assess and continuity for restoration of energy supplies during outage and impact emergencies. Continuation of these efforts will help enable the energy sector to adapt to disruptions from increasingly frequent severe weather events.

V. Summary and Areas for Further Research

This report provides an overview of the literature discussing the potential direct and indirect impacts of climate change on the energy sector. Key direct impacts that were identified include:

- Changes in water availability, and the timing of water availability, for both hydropower generation and thermal power plant cooling
- Impact of temperature changes on thermal power plant efficiency
- Impact of changes in cloud cover, wind resources and growing seasons on renewable resources
- Impact of sea level rise on existing energy infrastructure located along the coast, and new infrastructure siting options
- Impact of rising temperature on access to fossil fuel resources in Arctic regions\
- Impact of changes in storm frequency and intensity on vulnerable energy infrastructure (oil and gas infrastructure in and around the Gulf of Mexico, power lines throughout the world), the continuity of energy supply, and energy price volatility
- Increased T&D line losses due to elevated temperatures, and increased occurrence of blackouts resulting from line sagging

While some of these impacts have received considerable attention on their own, the body of literature that addresses them collectively is relatively new, with little done in the way of quantitative analysis. A couple of conclusions regarding broad, major potential climate impacts can, however, be gleaned from the literature. First, while the impact of climate change on hydropower generation is highly dependent on local conditions, the IPCC infers that available generating capacity will decrease at most major hydropower stations, resulting in an overall increase in the need for thermal generation. However, reduced water supply for hydropower generation generally implies reductions in the amount of cooling water available to thermal power plants. Within the U.S., available climate projections indicate that the Ohio River Valley, along with many parts of the West, may face drier conditions as a result of climate change. Thermal power plants in these regions may need to consider adaptation measures designed to reduce water requirements, including dry cooling and other cooling technologies under development at NETL.

And second, extreme northern and southern latitudes are likely to be disproportionately affected by climate change. This is a crucial point from an energy perspective, because the Arctic in particular is a significant source of current fossil fuel production, and may become a much bigger source in the future. However, in many cases the potential effects of climate change on energy exploration and production in the north tend to be uncertain and to offset one another, making it difficult to ascertain the likely overall impact. For example, earlier seasonal melting of the permafrost has reduced the timeframe during which vehicles can use ice roads, thereby reducing access to oil and gas resources. On the other hand, retreating sea-ice cover is expected to increase the navigation season for Arctic shipping routes, which could dramatically improve access not only to current fossil fuel resources, but potential future resources (methane hydrates).

It must, however, be stressed that improved shipping access is not a given, as year-to-year variability in ice conditions and increased occurrence of icebergs could make navigation more difficult. Climate projections indicate the potential for decreased water flow in the Athabasca River, which could limit the water supply needed to support future oil sands production.

Chapter III of this report identifies and discusses the effects of climate change that may "ripple" out from the agricultural, residential, commercial, industrial, and transportation sectors, to the energy sector. The indirect impacts of climate change on the energy sector, through its impact on other sectors, are numerous and varied, and may ultimately prove to be more significant than the direct impacts. However, it is even more difficult to ascertain the collective impact of climate change for these indirect effects, than it is for the direct effects. We can, however, glean from the general overview presented in Section III a few potential indirect effects that, even when considered in isolation, are likely to have a major impact on energy. First, regional shifts in the productivity of agricultural lands could have a major impact on global trade patterns and on transportation energy use. More specifically, it is likely that more energy will be required to transport agricultural products from areas of higher productivity to areas that face food shortages resulting from climate change. These same regional shifts in agricultural productivity may also trigger large-scale migrations, with potentially enormous implications for future energy supply and demand. While the literature does discuss the potential for climate-induced population migration, particularly from tropical and subtropical zones in Africa and Asia, there is little available discussion of the potential implications for energy. We might, however, infer that large-scale South-to-North migrations could lead to a shift in the global fuel and energy technology mix, e.g., from less-efficient to more advanced supply technologies. At the same time, overall global energy demand could increase, assuming immigrants from developing nations are effectively assimilated into the economies of developed countries. Alternatively, if population migration were to lead to conflict rather than assimilation, the result could be significant declines in global economic production and energy use; (although energy demand could increase temporarily during the conflicts).

In the case of the residential and commercial sectors, the main indirect impact of climate change on energy is likely to occur through its effect on space heating and cooling demand. The available studies indicate that, for the U.S., the increase in demand for space cooling is likely to offset the demand reduction for space heating, resulting in an overall increase in energy requirements. Increased consumer expenditures associated with this demand increase have been projected to reach $40 billion by 2100.[125] Literature assessing the impact of changes in space heating and cooling demand on energy outside the U.S. is limited, although one study projects an overall decline in energy demand for the United Kingdom.[126]

Finally, in the case of the industrial and transportation sectors, the macroeconomic impact of climate change on global GDP, and on the regional distribution of industrial production, is likely to hold the largest implications for energy. In particular, if the overall impact of climate change

[125] Mansur, E., Mendelsohn, R., Morrison, W. "A Discrete-Continuous Choice Model of Climate Change Impacts on Energy." Yale SOM Working Paper No. ES-43. March 14, 2005. Available at: http://ssrn.com/abstract=738544. Accessed 6/16/07.

[126] Jan F. Feenstra *et al*., *UNEP/IVM Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, Chapter 11 – Energy, Frank Stern, UNEP/IVM, 1998.

is a contraction in economic output, we can expect a corresponding decline in the total amount of energy used both to produce and transport goods.

Chapter IV discussed the potential, offered by a number of NETL R&D initiatives, to alleviate some of the negative impacts of climate change on the energy sector. Specific initiatives considered include the water-related activities under the IEP program, the Gasification Technologies Program, carbon capture and storage (CCS), the Modern Grid Initiative, and the Oil and Natural Gas Program. Both IGCC and the IEP water-related initiatives may provide adaptive value in regions that could face water shortages as a result of climate change. Water requirements for IGCC power plants are significantly less than those for other fossil plants, while various initiatives under the IEP program are designed to reduce power plant water consumption and to enable substitution of non-traditional water sources (e.g., coal mine discharge water, municipal wastewater, and ash pond effluent) for current freshwater sources. While CCS is a climate change mitigation technology, not an adaptation technology, it is most likely to prove commercially viable when deployed in conjunction with IGCC. By significantly reducing the GHG emissions associated with IGCC, it may help to foster the commercial application of IGCC—which *does* offer significant adaptive value. The Modern Grid Initiative incorporates a number of elements (e.g., integrated communications, sensing and measurement, advanced control methods, high-temperature superconductive power cables, and distributed generators) that will work to reduce the vulnerability of the grid to weather-induced damage, and increase its resiliency when damage does occur.

At least four activities within the Oil and Natural Gas Program appear to offer significant adaptive value. First, NETL's produced water treatment research is providing new sources of water in arid and semi-arid regions. As water regimes change, produced water may become a valuable contributor to community water supplies. NETL's Alaska Tundra Model project is helping efforts to adapt to *currently ongoing* climate change, which has reduced the time available for overland tundra travel, exploration and production activities in Alaska's North Slope. The goal of this project is to replace the existing, arbitrarily set guidelines for tundra travel with ones that better reflect actual conditions, and that will enable a safe extension of the travel season. NETL's methane hydrates research program is focused on overcoming the barriers to methane hydrate production. Methane hydrates represent a massive potential source of methane that could help to increase supplies and lower the price of natural gas, thereby fostering the application of natural gas fuel cells as distributed generators in a modernized, less vulnerable and more resilient grid. Finally, NETL's Energy Infrastructure Analysis Group helps to provide Federal agencies with the up-to-date information needed to protect energy supply and the energy infrastructure in the event of emergencies, including severe weather emergencies.

Recommendations for Further Work

The assessment of both the potential impacts of climate change on the energy sector and the potential value of NETL's R&D in alleviating some of these impacts, presented in this report, is primarily qualitative and speculative in nature. This reflects not only the fact that the sectoral impacts of climate change is a relatively new area of research, but also the highly complex nature of the interactions. The potential impacts of climate change on the energy sector are so numerous and varied,, and so intertwined with economy-wide impacts, that merely identifying the second and third order effects, let alone quantifying them, is difficult.. The difficulties are compounded by the high degree of uncertainty surrounding projections of basic climate variables, such as temperature and precipitation. Given the complexities, it is safe to say that an attempt to conduct a definitive, comprehensive, quantitative analysis of all of the potential impacts of climate change on the electricity sector would be premature at this point in time.

That said a more limited, focused effort designed to at least begin a quantification of the adaptive value of NETL's R&D appears both feasible and useful. Ultimately it will prove important to quantify the added value of NETL's R&D programs under a warmer climate, so as to ensure that NETL's benefit assessments are comprehensive and do not underestimate the full future value of the R&D. While even a limited, partial effort at quantifying adaptive value will likely prove very challenging, such an effort would represent an important first step in highlighting the heightened relevance and importance of NETL's R&D under possible future climate change scenarios. As part of Deliverable 6 under this same Task assignment, RDS proposed a "first-step" effort to assess the adaptive value of NETL's IEP water-related initiatives. As this proposed effort is highly relevant to the subject of this report, we have included our detailed recommendation, adapted from Deliverable 6, in the following pages.

The IEP water-related R&D activity has a goal of significantly reducing freshwater withdrawal and consumption rates. How might the added adaptive value of this activity be assessed? Ideally, we would begin with robust projections of available water supply, demand and costs for all sectors, including the power sector, in the absence of climate change. Costs would include not only direct costs of water usage, but also any indirect costs to the economy resulting from supply constraints (e.g., the costs to the economy of taking agricultural lands out of production due to inadequate water availability). Separate projections would be available "with" and "without" the impact of NETL's water-energy R&D on water demand; a comparison of the costs for the two projections would yield an estimate of the monetary benefit of NETL's water-energy R&D under the assumption that the climate remains unchanged. These projections would then be used as baselines for the development of new projections that would account for the impacts of climate change on water supply, demand, and costs. The difference between the "with R&D" projection and the "without R&D" projection would yield an estimate of the R&D benefits with climate change.

This analysis is, however, much easier described than done. For one, we do not in fact possess projections, robust or otherwise, of water supply, demand, and costs with or without the impact of NETL's R&D. In fact, we lack even the most fundamental data that would be needed to develop such projections. Most importantly, national water availability has not been comprehensively assessed in 25 years.[127] Thus *current* water supply, let alone future supply, is unknown for the country as a whole.

Furthermore, projecting the potential impacts of climate change on water supply, water demand, electricity demand, and electricity supply would be a very challenging undertaking. The potential interactions between precipitation and temperature change, on the one hand, and water

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[127] Gary J. Stiegel, Jr., Andrea McNemar, Michael Nemeth, Brian Schimmoller, James Murphy, and Lynn Manfredo, "Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements," DOE/NETL-2006/1235, August 2006, p. 7.

supply, water demand, electricity demand, and electricity supply are numerous, interdependent, and complex. Potential interactions include the following:

- Reductions in precipitation in some regions may directly impact available water supply
- Changes in the timing of snow melt may shift water availability seasonally
- Reductions in river flow rates may reduce hydropower generation, necessitating an increase in fossil fuel capacity and a commensurate increase in water cooling needs
- Reductions in water availability may indirectly affect electricity demand through its impact on other sectors; e.g., increased reliance on irrigation could increase electricity demand for water pumping, while at the same time reducing water available for power plant cooling needs
- The overall impact of climate change on industrial production and macroeconomic growth may reduce electricity demand, thereby reducing power plant water requirements
- Higher temperatures may reduce water availability by increasing evaporation from surface-water sources
- Higher temperatures may increase electricity demand for space cooling, thereby increasing demand for power plant cooling water
- Higher temperatures may adversely impact power plant performance.

Given the complexity of these interrelationships and the fact that many of them are poorly understood, RDS recommends a phased approach to any attempt to quantify the added adaptive value of NETL's water-energy R&D. Attempts should be made to quantify some of the simpler, more direct relationships between climate change and the power sector, before proceeding to the indirect, more complex interrelationships. Furthermore, given the lack of comprehensive national data on water availability, RDS recommends a regional case study approach rather than an attempt to assess adaptive value for the country as a whole. A region or locality that appears to face particularly severe water availability constraints might be selected, along with another region that may face less severe, but still significant, water availability issues. It is important to consider regions facing different degrees of water constraints, because the power plant cooling technologies applicable to a severely constrained region might differ from the technologies best-suited for a region with lesser constraints (e.g., dry cooling might be applicable to the former but not the latter region). Each case study region should be analyzed under two or three alternative climate scenarios, to capture the uncertainties in regional climate modeling. A regional case study would involve the following steps or subtasks:

- Subtask 1: Selection of 2 case study regions. In addition to selecting the regions based on their water availability outlook, it would be important to pick regions with a wealth of water- and energy-related information, and for which climate projections can be obtained. Subtask 1 would therefore include a preliminary assessment of the availability of data and projections for potential candidate regions.
- Subtask 2: Data Collection and Development. Data and information to be collected or estimated would include, e.g., water supply data (including a detailed characterization of

all major water supply sources), seasonal precipitation and river flow data, water demand by sector, projections of future water demand by sector (or, alternatively, regional economic and population growth projections that could be used to construct water demand projections), electricity demand and projected demand growth, and a detailed inventory of existing and planned generating capacity by plant type. In addition, historical time series data that would help to relate changes in water supply and demand to changes in precipitation and temperature would be needed, including, e.g., historical data on seasonal temperatures, precipitation, reservoir and river levels, river flow rates, hydropower generation, water usage by sector, etc. Finally, alternative climate (temperature and precipitation) projections for the regions would be obtained (e.g., from the Hadley Center).

- Subtask 3: Algorithm and Spreadsheet Model Development. The historical data collected in Subtask 2 would be used to estimate equations relating, e.g., precipitation to reservoir levels and river flow rates, temperature to evaporative losses, sectoral water demand to precipitation and temperature, electricity demand to temperature and precipitation, etc. In cases where data sufficient for equation estimation are lacking, attempts would be made to obtain default algorithms from the literature. Again, in a first phase case study, the focus would be on estimating *direct* effects of temperature and precipitation on water supply/demand and electricity supply/demand; indirect effects, while potentially very important, would be deferred to a follow-on analysis. The algorithms would be combined into a simple spreadsheet model for use in subsequent subtasks.
- Subtask 4: Climate Impact Assessment. The spreadsheet model developed in Subtask 3 would be used to estimate changes in electricity and water supply/demand under two or three alternative climate scenarios. These changes would then be applied to the electricity and water projections gathered during Subtask 1 to obtain new projections modified to capture the impact of climate change.
- Subtask 5: Estimation of Impact of NETL R&D. Finally, using the detailed projections of electricity generating capacity and generation by power plant type, along with NETL's estimates of the potential impacts of new cooling technologies on water withdrawals and consumption, an estimate of the reduction in water demand attainable through the optimal deployment of these technologies would be developed for each case study region and climate scenario. By applying this reduction estimate to the water projections from Subtasks 1 and 4, the impact of the new cooling technologies on water supply, with and without climate change, would be obtained. The resulting improvements in water availability would yield an estimate of the added adaptive value of the new technologies, which could be compared with NETL's projected costs for the technologies.
- Subtask 6: Documentation. The methodologies, model and case study results would be documented comprehensively and in detail.

Obviously, the ability to complete the above-outlined effort would depend heavily on the availability and quality of water resource and energy data for the selected regions. For example, our ability to monetize the benefits would depend on the availability of water cost and usage data. However, even if a monetized benefit estimate proves unattainable, an estimate of the impact of NETL's energy-water R&D on water requirements, and the adequacy of available supply to meet those requirements, should prove very useful. For one, such estimates would help

NETL to prioritize its R&D efforts. Furthermore, were the results to indicate that, through the deployment of NETL technologies, water supply and demand could be brought back into balance in one or two regions that would otherwise face an unsustainable situation, this alone would provide strong evidence supporting the value of the R&D activity.

It would be important to caveat the results of such an effort, in so far as only the direct effects of climate change on the water-energy interface would be considered. However, if the case study were to prove successful, it might be possible to extend the analysis in a "second phase" effort to include some of the indirect effects. Given the complexity of the interrelationships between climate, energy, water, other sectors such as agriculture, and the broader economy, RDS strongly recommends such a phased approach, in which the "lessons learned" from the earlier efforts can be digested and used to extend and strengthen subsequent analyses.