CHAPTER 3

Effects of Climate Change on Energy Production and Distribution in the United States

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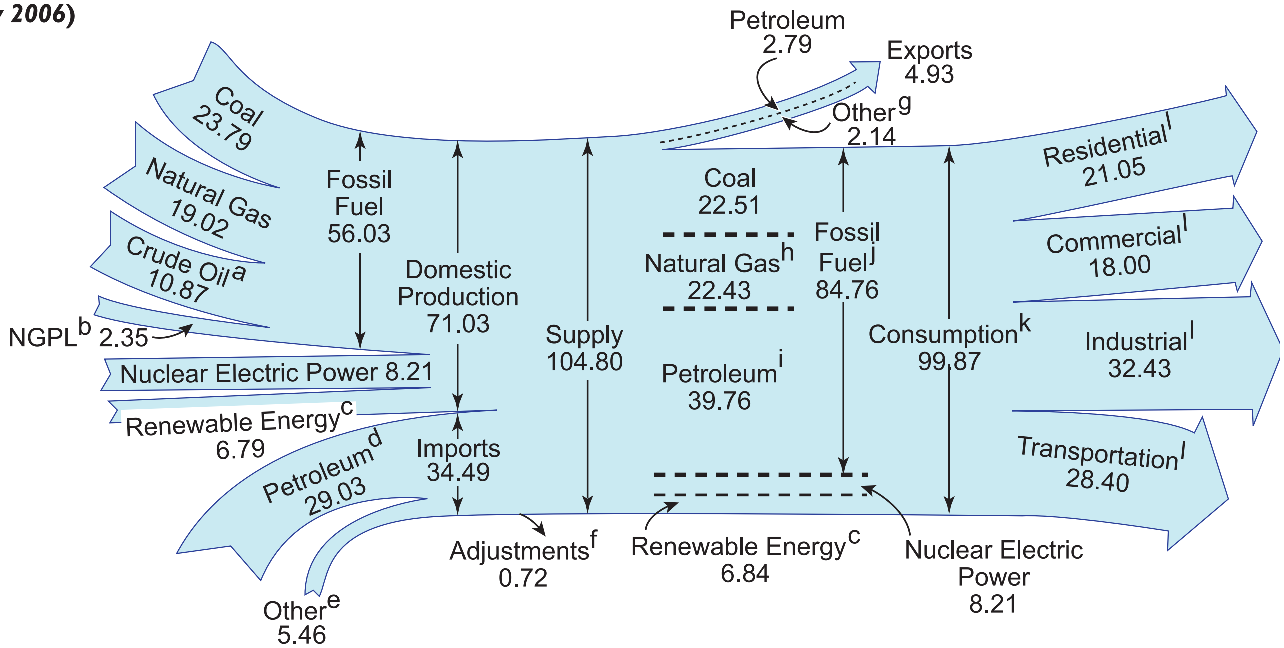
Energy production in the U.S. is dominated by fossil fuels: coal, petroleum, and natural gas (Fig. 3.1). Every existing source of energy in the United States has some vulnerability to climate variability (Table 3.1). Renewable energy sources tend to be more sensitive to climate variables; but fossil energy production can also be adversely effected by air and water temperatures, and the thermoelectric cooling process that is critical to maintaining high electrical generation efficiencies also applies to nuclear energy. In addition, extreme weather events have adverse effects on energy production, distribution, and fuel transportation.

This chapter discusses impacts on energy production and distribution in the United States associated with projected changes in temperature, precipitation, water resources, severe weather events, and sea level rise, although the currently available research literatures tend to be limited in most cases. Overall, the effects on the existing infrastructure might be categorized as modest; however, local and industry-specific impacts could be large, especially in areas that may be prone to disproportional warming (Alaska) or weather disruptions (Gulf Coast and Gulf of Mexico). The existing assemblage of power plants and distribution systems is likely to be more affected by ongoing unidirectional changes, compared with possible future systems, if future systems can be designed with the upfront flexibility to accommodate the span of potential impacts. Possible adaptation measures include technologies that minimize the impact of increases in ambient temperatures on power plant equipment, technologies that conserve water use for power plant cooling processes, planning at the local and regional level to anticipate storm and drought impacts, improved forecasting of the impacts of global warming on renewable energy sources at regional and local levels, and establishing action plans and policies that conserve both energy and water.

Figure 3.1. Energy Flow in the U.S. (EIA, *Annual Energy Review 2006*)

Energy Flow, 2006
(Quadrillion Btu)



[a]Includes lease condensate.
[b]Natural gas plant liquids.
[c]Conventional hydroelectric power, biomass, geothermal, solar/PV, and wind.
[d]Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[e]Natural gas, coal, coal coke, fuel ethanol, and electricity.
[f]Stock changes, losses, gains, miscellaneous blending components, and unaccounted-for supply.
[g]Coal, natural gas, coal coke, and electricity.
[h]Natural gas only; excludes supplemental gaseous fuels.
[i]Petroleum products, including natural gas plant liquids and crude oil burned as fuel.
[j]Includes 0.06 quadrillion Btu of coal coke net imports.
[k]Includes 0.06 quadrillion Btu of electricity net imports.
[l]Primary consumption, electricity retail sales, and electrical systems energy losses, which are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales.

Notes: •Data are preliminary. •Values are derived from the source data prior to rounding for publication. •Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, 2.1a, and 10.1.

3.1 EFFECTS ON FOSSIL AND NUCLEAR ENERGY

Climate change can affect fossil and nuclear energy production, conversion, and end-user delivery in a myriad of ways. Average ambient temperatures impact the supply response to changes in heating and cooling demand by affecting generation cycle efficiency, along with cooling water requirements in the electrical sector, water requirements for energy production and refining, and Gulf of Mexico (GOM) produced water discharge requirements. Often these impacts appear "small" based on the change in system efficiency or the potential reduction in reliability, but the scale of the energy industry is vast: fossil fuel-based net electricity generation exceeded 2,500 billion kWh in 2004 (EIA 2006). A net reduction in generation of 1% due to increased ambient temperature (Maulbetsch and DiFilippo 2006) would represent a drop in supply of 25 billion kWh that might need to be replaced somehow. The GOM temperature-related issue is a result of the formation of water temperature-related anoxic zones and is important because that region accounts for 20 to 30% of the total domestic oil and gas production in the U.S. (Figure 3.2). Constraints on produced water discharges could increase costs and reduce production, both in the GOM region and elsewhere. Impacts of extreme weather events could range from localized railroad track distortions due to temperature extremes, to regional-scale coastal flooding from hurricanes, to watershed-scale river flow excursions from weather variations superimposed upon, or possibly augmented by, climate change. Spatial scale can range from kilometers to continent-scale; temporal scale can range from hours to multiyear. Energy impacts of episodic events can linger for months or years, as illustrated by the continuing loss of oil and

Table 3-1. Mechanisms Of Climate Impacts On Various Energy Supplies In The U.S. Percentages Shown Are Of Total Domestic Consumption; (T = water/air temperature, W = wind, H = humidity, P = precipitation, and E = extreme weather events)

Energy Impact Supplies		Climate Impact Mechanisms
Fossil Fuels (86%)	Coal (22%)	Cooling water quantity and quality (T), cooling efficiency (T, W, H), erosion in surface mining
	Natural Gas (23%)	Cooling water quantity and quality (T), cooling efficiency (T, W, H), disruptions of off-shore extraction (E)
	Petroleum (40%)	Cooling water quantity and quality, cooling efficiency (T, W, H), disruptions of off-shore extraction and transport (E)
	Liquified Natural Gas (1%)	Disruptions of import operations (E)
Nuclear (8%)		Cooling water quantity and quality (T), cooling efficiency (T, W, H)
Renewables (6%)	Hydropower	Water availability and quality, temperature-related stresses, operational modification from extreme weather (floods/droughts), (T, E)
	Biomass	
	• Wood and forest products	Possible short-term impacts from timber kills or long-term impacts from timber kills and changes in tree growth rates (T, P, H, E, carbon dioxide levels)
	• Waste (municipal solid waste, landfill gas, etc.)	n/a
	• Agricultural resources (including derived biofuels)	Changes in food crop residue and dedicated energy crop growth rates (T, P, E, H, carbon dioxide levels)
	Wind	Wind resource changes (intensity and duration), damage from extreme weather
	Solar	Insolation changes (clouds), damage from extreme weather
	Geothermal	Cooling efficiency for air-cooled geothermal (T)
(Source: EIA, 2004)		

gas production in the GOM (MMS 2006a, 2006b, and 2006c) eight months after the 2005 hurricanes.

3.1.1 Thermoelectric Power Generation

Climate change impacts on electricity generation at fossil and nuclear power plants are likely to be similar. The most direct climate impacts are related to power plant cooling and water availability.

Projected changes in water availability throughout the world would directly affect the availability of water to existing power plants. While there is uncertainty in the nature and amount of the change in water availability in specific locations, there is agreement among climate models that there will be a redistribution of water, as well as changes in the availability by season. As currently designed, power plants require significant amounts of water, and they will be vulnerable to fluctuations in water supply. Regional-scale changes would likely mean that some areas would see significant increases in water availability, while other regions would see significant decreases. In those areas seeing a decline, the impact on power plant availability or even siting of new capacity could be significant. Plant designs are flexible and new technologies for water reuse, heat rejection, and use of alternative water sources are being developed; but, at present, some impact—significant on a local level—can be foreseen. An example of such a potential local effect is provided in Box 3.1—Chattanooga: A Case Study, which shows how

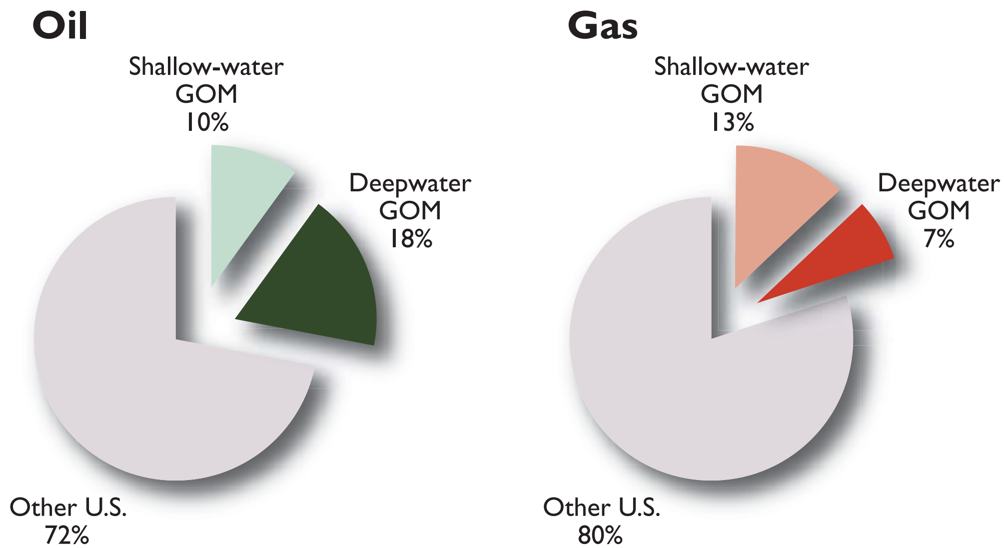


Figure 3.2. Distribution Of Off-Shore Oil And Gas Wells In The Gulf Of Mexico (GOM) And Elsewhere In The U.S.

cooling conditions might evolve over the 21st century for generation in one locality. Situations where the development of new power plants is being slowed down or halted due to inadequate cooling water are becoming more frequent throughout the U.S. (SNL, 2006b).

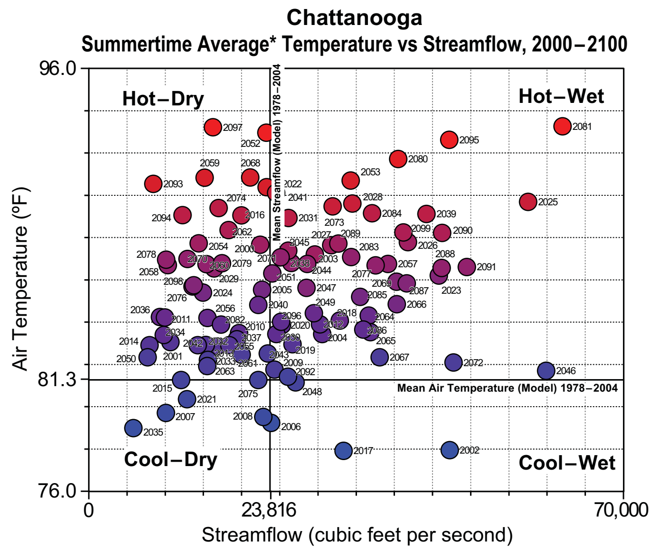
In those areas seeing an increase in stream flows and rainfall, impacts on groundwater levels and on seasonal flooding could have a different set of impacts. For existing plants, these impacts could include increased costs to manage on-site drainage and run-off, changes in coal handling due to increased moisture content or additional energy requirements for coal drying, etc. The following excerpt details the magnitude of the intersection between energy production and water use.

An October 2005 report produced by the National Energy Technology Laboratory stated, in part, that the production of energy from fossil fuels (coal, oil, and natural gas) is inextricably linked to the availability of adequate and sustainable supplies of water. While providing the United States with a majority of its annual energy needs, fossil fuels also place a high demand on the Nation's water resources in terms of both use and quality impacts (EIA, 2005d). Thermoelectric generation is water intensive; on average, each kWh of electricity generated via the steam cycle requires approximately 25 gallons of water, a weighted average that captures total thermoelectric water withdrawals and generation for both once-through and recirculating cooling systems. According to the United States Geological Survey (USGS), power plants rank only slightly behind irrigation in terms of freshwater withdrawals in the United States (USGS, 2004), although irrigation withdrawals tend to be more consumptive. Water is also required in the mining, processing, and transportation of coal to generate electricity all of which can have direct impacts on water quality. Surface and underground coal mining can result in acidic, metal-laden water that must be treated before it can be discharged to nearby rivers and streams. In addition, the USGS estimates that in 2000 the mining industry withdrew approximately 2 billion gallons per day of freshwater. Although not directly related to water quality, about 10% of total U.S. coal shipments were delivered by barge in 2003 (USGS, 2004). Consequently, low river flows can create shortfalls in coal inventories at power plants.

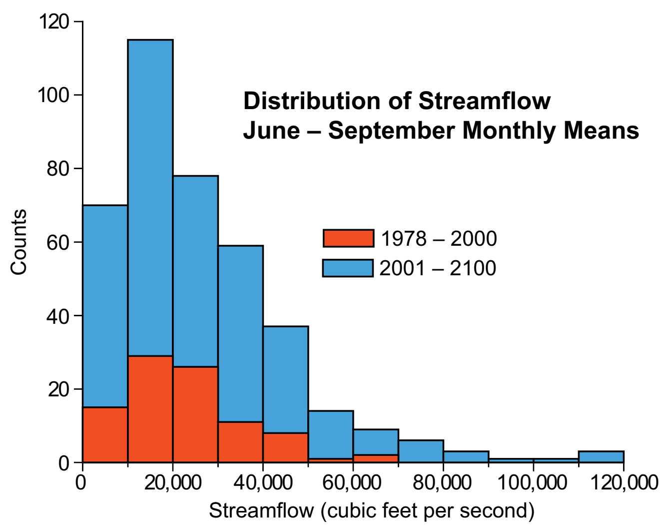
Freshwater availability is also a critical limiting factor in economic development and sustainability, which directly impacts electric-power supply. A 2003 study conducted by the Government Accountability Office indicates that 36 states anticipate water shortages in the next 10 years under normal water conditions, and 46 states expect water shortages under drought conditions (GAO 2003). Water supply and demand estimates by the Electric Power Research Institute (EPRI) for the years 1995 and 2025 also indicate a high likelihood of local and regional water shortages in the United States (EPRI 2003). The area that is expected to face the most serious water constraints is the arid southwestern United States.

BOX 3.1 Chattanooga: A Case Study of Cooling Effects

A preliminary analysis of one IPCC climate change scenario (A1B) provides one example of how cooling conditions might evolve over the 21st century for generation in the Chattanooga vicinity (ORNL work in progress). In this example, a slight upward trend in stream flow would provide a marginal benefit for once-through cooling, but would be offset by increasing summertime air temperatures that trigger limits on cooling water intake and downstream mixed temperatures. Closed-cycle cooling would also become less effective as ambient temperature and humidity increased. Utilities would need to maintain generation capacity by upgrading existing cooling systems or shifting generation to newer facilities with more cooling capacity. Without technology-based improvements in cooling system energy efficiency or steam-cycle efficiency, overall thermoelectric generation efficiency would decrease.



*Mean of June – September monthly mean values



In any event, the demand for water for thermoelectric generation will increasingly compete with demands from other sectors of the economy such as agriculture, residential, commercial, industrial, mining, and in-stream use. EPRI projects a potential for future constraints on thermoelectric power in 2025 for Arizona, Utah, Texas, Louisiana, Georgia, Alabama, Florida, and all of the Pacific Coast states. Competition over water in the western United States, including water needed for power plants, led to a 2003 Department of Interior initiative to predict, prevent, and alleviate water-supply conflicts (DOI 2003). Other areas of the United States are also susceptible to freshwater shortages as a result of drought conditions, growing populations, and increasing demand.

Concerns about water supply expressed by state regulators, local decision-makers, and the general public are already impacting power projects across the United States. For example, Arizona recently rejected permitting for a proposed power plant because of concerns about how much water it would withdraw from a local aquifer (Land Letter 2004). An existing Entergy plant located in New York is being required to install a closed-cycle cooling water system to prevent fish deaths resulting from operation of its once-through cooling water system (Greenwire, 2003). Water availability has also been identified by several Southern States Energy Board member states as a key factor in the permitting process for new merchant power plants (Clean Air Task Force 2004). In early 2005, Governor Mike Rounds of South Dakota called for a summit to discuss drought-induced low flows on the Missouri River and the impacts on irrigation, drinking-water systems, and power plants (Billingsgazette.com 2005). Residents of Washoe County, Nevada expressed opposition to a proposed coal-fired power plant in light of concerns about how much water the plant would use (Reno-Gazette Journal. 2005). Another coal-fired power plant to be built in Wisconsin on Lake Michigan has been under attack from environmental groups because of potential effects of the facility's cooling-water-intake structures on the Lake's aquatic life (Milwaukee Journal Sentinel, 2005).

Such events point toward a likely future of increased conflicts and competition for the water the power industry will need to operate their thermoelectric generation capacity. These conflicts will be national in scope, but regionally driven. It is likely that power plants in the west will be confronted with issues related to water rights: that is, who owns the water and the impacts of chronic and sporadic drought. In the east, current and future environmental requirements, such as the Clean Water Act's intake structure regulation, could be the most significant impediment to securing sufficient water, although local drought conditions can also impact water availability. If changing climatic conditions affect historical patterns of precipitation, this may further complicate operations of existing plants, and the design and site selection of new units.

EIA 2004a reports net summer and winter capacity for existing generating capacity by fuel source. Coal-fired and nuclear plants have summer/winter ratios of 0.99 and 0.98 and average plant sizes of 220 MW and 1015 MW, respectively. Petroleum, natural gas, and dual fuel-fired plants show summer/winter net capacity ratios of 0.90 to 0.93, indicating higher sensitivity to ambient temperature. Average sizes of these plants ranged from 12 MW to 84 MW, consistent with their being largely peaking and intermediate load units. Although large coal and nuclear generating plants report little degradation of net generating capacity from winter to summer conditions, there are reports (University of Missouri-Columbia 2004) of plant derating and shutdowns caused by temperature-related river water level changes and thermal limits on water discharges. Actual generation in 2004 (EIA, 2004a) shows coal-fired units with 32% of installed capacity provided 49.8% of generation and nuclear units with 10% of installed capacity provided 17.8% of power generated, indicating that these sources are much more heavily dispatched than are petroleum, natural gas, and dual-fired sources. To date, this difference has been generally attributed to the lower variable costs of coal and nuclear generation, indicating that the lower average dispatch has been more driven by fuel costs than temperature-related capacity constraints.

Gas turbines, in their varied configurations, provide about 20% of the electric power produced in the U.S. (EIA 2006). Gas turbines in natural gas simple cycle, combined cycle (gas and steam turbine), and coal-based integrated gasification combined cycle applications are affected by local ambient conditions, largely local ambient temperature and pressure. Ambient temperature and pressure have an immediate impact on gas turbine performance. Turbine performance is measured in terms of heat rate (efficiency) and power output. Davcock et al. (Davcock, DesJardins, and Fennell 2004) found that a 60°F increase in ambient temperature, as might be experienced daily in a desert environment, would have a 1-2 percentage point reduction in efficiency and a 20-25% reduction in power output. This effect is nearly linear; so a 10 degree Fahrenheit increase in ambient temperature would produce as much as a 0.5 percentage point reduction in efficiency and a 3-4% reduction in power output in an existing gas turbine. Therefore, the impact of potential climate change on the fleet of existing turbines would be driven by the impact that small changes in overall performance would have on both the total capacity available at any time and the actual cost of electricity.

Turbines for NGCC and IGCC facilities are designed to run 24 hours, 7 days a week; but simple cycle turbines used in topping and intermediate service are designed for frequent startups and rapid ramp rates to accommodate grid dispatch requirements. Local ambient temperature conditions will normally vary by 10 – 20°F on a 24-hour cycle, and many temperate-zone areas have winter-summer swings in average ambient temperature of 25-35°F. Consequently, any long-term climate change that would impact ambient temperature is believed to be on a scale within the design envelope of currently deployed turbines. As noted earlier, both turbine power output and efficiency vary with ambient temperature deviation from the design point. The primary impacts of longer periods of off-design operation will be modestly reduced capacity and reduced efficiency. Currently turbine-based power plants are deployed around the world in a wide variety of ambient conditions and applications, indicating that new installations can be designed to address long-term changes in operating conditions. In response to the range of operating temperatures and pressures to which gas turbines are being subjected, turbine designers have developed a host of tools for dealing with daily and local ambient conditions. These tools include inlet guide vanes, inlet air fogging (essentially cooling and mass flow addition), inlet air filters, and compressor blade washing techniques (to deal with salt and dust deposited on compressor blades). Such tools could also be deployed to address changes in ambient conditions brought about by long-term climate change.

3.1.2 Energy Resource Production And Delivery

Other than for renewable energy sources, energy resource production and delivery systems are mainly vulnerable to effects of sea level rise and extreme weather events.

IPCC 2001a projected a 50-cm. (20-in.) rise in sea level around North America in the next century from climate change alone. This is well within the normal tidal range and would not have any significant effect on off-shore oil and gas activities. On-shore oil and gas activities could be much more impacted, which could create derivative impacts on off-shore activities.

A number of operational power plants are sited at elevations of 3 ft or less, making them vulnerable to these rising sea levels. In addition, low-lying coastal regions are being considered for the siting of new plants due to the obvious advantages in delivering fuel and other necessary feedstocks. Significant percentages of other energy infrastructure assets are located in these same areas, including a number of the nation's oil refineries as well as most coal import/export facilities and liquefied natural gas terminals. Given that a large percentage of the nation’s energy infrastructure lies along the coast, rising sea levels could lead to direct losses such as equipment damage from flooding or erosion or indirect effects such as the costs of raising vulnerable assets to higher levels or building future energy projects further inland, thus increasing transportation costs.

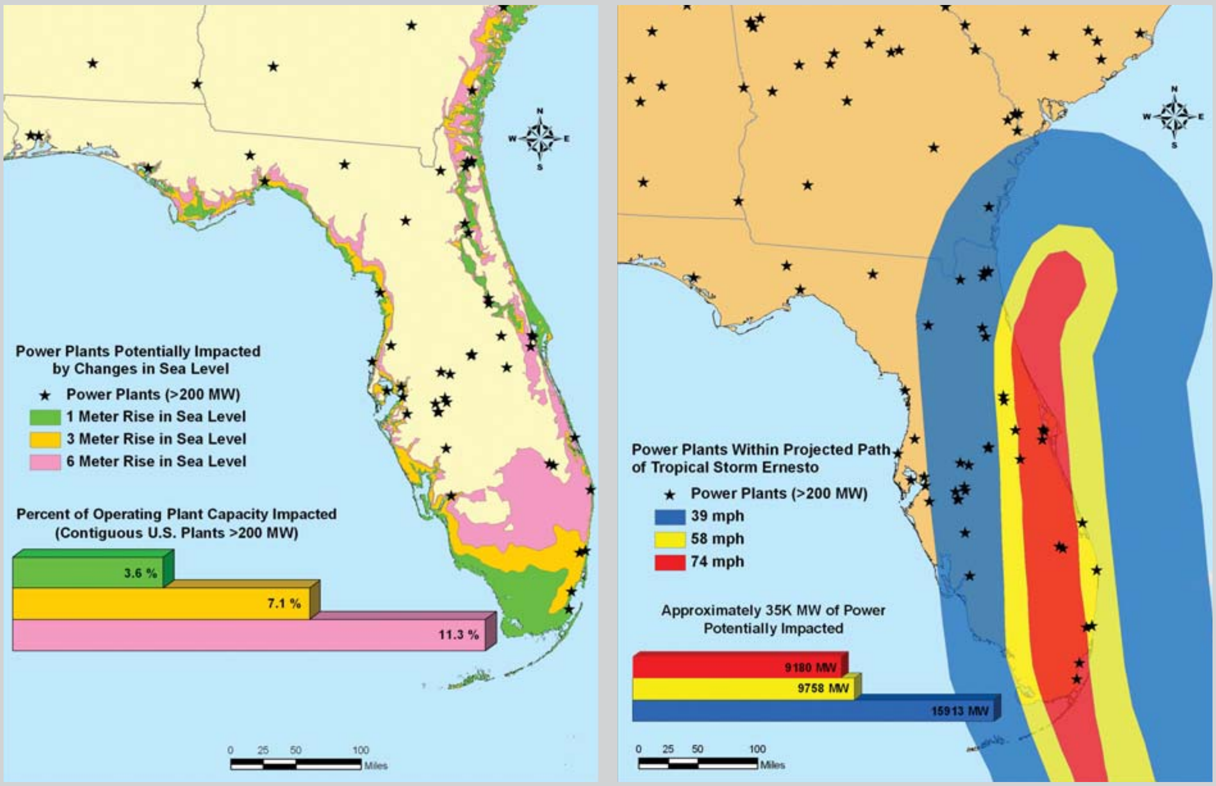
IPCC 2001a and USGS 2000 have identified substantial areas of the U.S. East Coast and Gulf Coast as being vulnerable to sea-level rise. Roughly one-third of U.S. refining and gas processing physical plant lies on coastal plains adjacent to the Gulf of Mexico (GOM), hence it is vulnerable to inundation, shoreline erosion, and storm surges. On-shore but noncoastal oil and gas production and processing activities may be impacted by climate change primarily as it impacts extreme weather events, phenomena not presently well understood. Florida’s energy infrastructure may be particularly susceptible to sea-level rise impacts. (See Box 3.2 Florida).

Alaska represents a special case for climate adaptation because the scale of projected impacts is expected to be greater in higher latitudes (See Box 3.3: A Case Study). Extreme weather events, which could represent more significant effects, are discussed in 3.1.4. Even coal production is susceptible to extreme weather events that can directly impact open-cast mining operations and coal cleaning operations of underground mines.

Potential impacts on novel energy resources are speculative at present. Oil shale resource development, which is considered to be water intensive, could be made more difficult if climate change further reduces annual precipitation in an already arid region that is home to the major

BOX 3.2 Florida

Florida's energy infrastructure may be particularly susceptible to sea-level rise impacts. Most of the petroleum products consumed in Florida are delivered by barge to three ports (NASEO, 2005) two on the East Coast of Florida and one on the West Coast. The interdependencies of natural gas distribution, transportation fuel distribution and delivery, and electrical generation and distribution were found to be major issues in Florida's recovery from multiple hurricanes in 2004. In addition, major installations such as nuclear power plants are located very close to the seacoast at elevations very close to sea level. The map on the left shows major power plants susceptible to sea-level rise in Florida. The map on the right illustrates power plants in the path of Tropical Storm Ernesto.



oil shale deposits. Water availability (Struck 2006) is beginning to be seen as a potential constraint on synthetic petroleum production from the Canadian oil sands. Coal-to-liquids operations also require significant quantities of water.

3.1.3 Transportation of Fuels

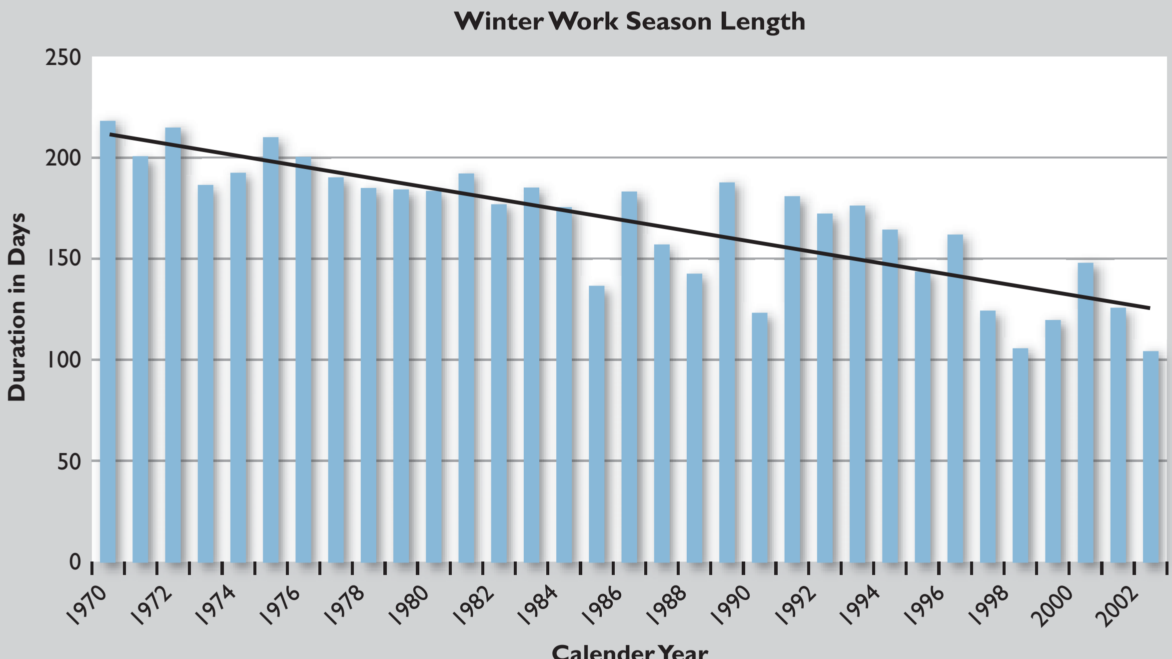
Roughly 65% of the petroleum products supplied in the Petroleum Administration for Defense (PAD) East Coast District (Figure 3.3) arrive via pipeline, barge, or ocean vessel (EIA 2004). Approximately 80% of the domestic-origin product is transported by pipeline. Certain areas, e.g., Florida, are nearly totally dependent on maritime (barge) transport. About 97% of the crude oil charged to PAD I refineries is imported, arriving primarily by ocean vessels. PAD II receives the bulk of its crude oil via pipeline, roughly two-thirds from PAD III and one-third from Canada. Both pipeline and barge transport have been susceptible to extreme weather events, with pipeline outages mostly driven by interdependencies with the electrical grid. In addition (see 3.3.2), increased ambient temperatures can degrade pipeline system performance, particularly when tied to enhanced oil recovery and, if practiced in the future, carbon sequestration. The transportation of coal to end users, primarily electrical generation facilities, is dependent on rail and barge transportation modes (EIA 2004b). Barge transport is

BOX 3.3 Alaska: A Case Study

Alaska represents a special case for climate adaptation where temperatures have risen (3°C) over the last few decades, a rate that is almost twice that of the rest of the world. Some models predict this warming trend will continue, with temperatures possibly rising as much as 4-7°C over the next 100 years (ACIA 2004).

In areas of Alaska's North Slope, change is already being observed. The number of days allowed for winter tundra travel dropped significantly since the state began to set the tundra opening date in 1969, and a chart of that decline has been widely used to illustrate one effect of a warming Arctic (Alaska Department of Natural Resources 2004). There is a significant economic impact on oil and natural gas exploration from a shorter tundra travel season, especially since exploration targets have moved farther away from the developed Prudhoe Bay infrastructure, requiring more time for ice road building. It is unlikely that the oil industry can implement successful exploration and development plans with a winter work season consistently less than 120 d.

Further, melting permafrost can cause subsidence of the soil, thereby threatening the structural integrity of infrastructure built upon it. It was anticipated that the Trans-Alaska Pipeline System would melt surrounding permafrost in the areas where it would be buried. Therefore, extensive soil sampling was conducted and



Source: ACIA, 2004.

in areas where permafrost soils were determined to be thaw-stable, conventional pipeline building techniques were utilized. But in ice-rich soils, the ground is generally not stable after the permafrost melts. Therefore, unique aboveground designs integrating thermal siphons were used to remove heat transferred in the permafrost via the pilings used to support the pipeline. And in a few selected areas where aboveground construction was not feasible, the ground around the pipeline is artificially chilled (U.S. Arctic Research Commission 2003 and Pipeline Engineering 2007). Such extensive soil testing and unique building techniques add substantial cost to large development projects undertaken in arctic climates but are necessary to ensure the long-term viability of the infrastructure.

Exploration in the Arctic may benefit from thinning sea ice. Recent studies indicate extent of sea ice covering the Arctic Ocean may have reduced as much as 10%, and thinned by as much as 15%, over the past few decades. These trends suggest improved shipping accessibility around the margins of the Arctic Basin with major implications for the delivery of goods as well as products such as LNG and oil from high latitude basins (ACIA 2004). A reduction in sea ice may also mean increased off-shore oil exploration (ACIA 2004).

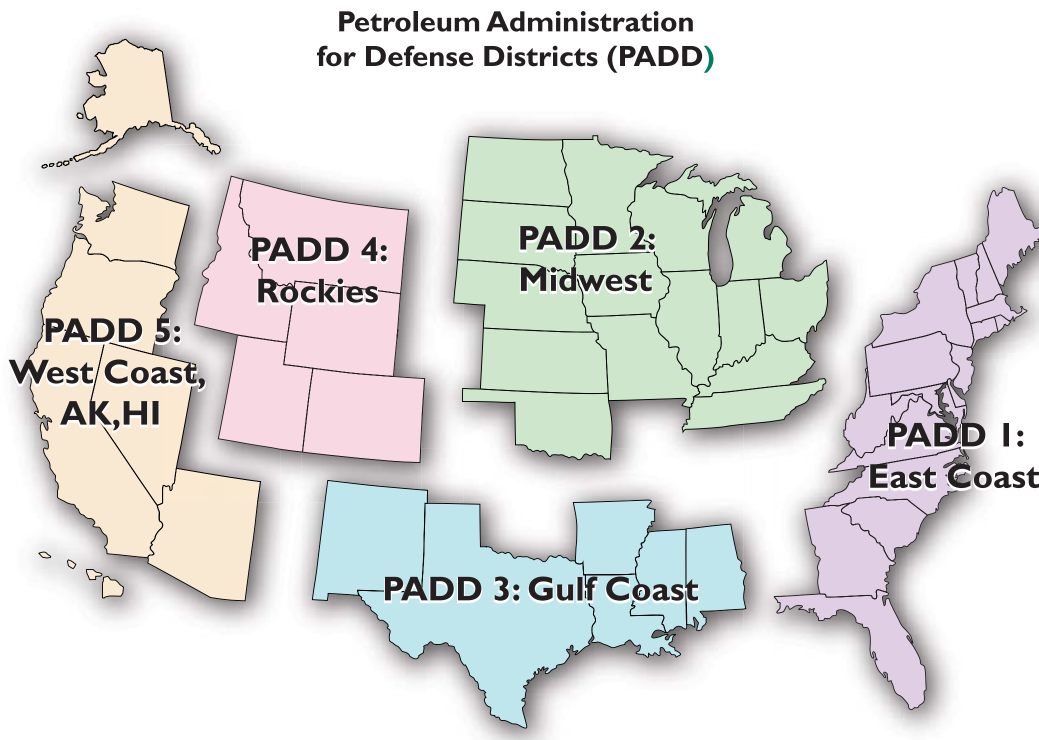


Figure 3.3. Petroleum Administration for Defense (PAD) Districts

susceptible to both short term, transient weather events and to longer-term shifts in regional precipitation and snow melt patterns that may reduce the extent of navigability of rivers and reduce or expand the annual navigable periods. In addition, offshore pipelines were impacted by Hurricane Ivan even before the arrival of Hurricanes Katrina and Rita (see 3.1.4).

3.1.4 Extreme Events

Climate change may cause significant shifts in current weather patterns and increase the severity and possibly the frequency of major storms (NRC 2002). As witnessed in 2005, hurricanes can have a debilitating impact on energy infrastructure. Direct losses to the energy industry in 2005 are estimated at $15 billion (Marketwatch.com 2006), with millions more in restoration and recovery costs. Future energy projects located in storm prone areas will face increased capital costs of hardening their assets due to both legislative and insurance pressures. For example, the Yscloskey Gas Processing Plant was forced to close for 6 months following Hurricane Katrina, resulting in both lost revenues to the plant's owners and higher prices to consumers as alternative gas sources had to be procured. In general, the incapacitation of energy infrastructure – especially of refineries, gas processing plants and petroleum product terminals – is widely credited with driving a price spike in fuel prices across the country, which then in turn has national consequences. The potential impacts of more severe weather are not, in fact, limited to hurricane-prone areas. Rail transportation lines, which transport approximately 2/3 of the coal to the nation's power plants (EIA 2002), often closely follow riverbeds, especially in the Appalachian region. More severe rainstorms can lead to flooding of rivers that then can wash out or degrade the nearby roadbeds. Flooding may also disrupt the operation of inland waterways, the second-most important method of transporting coal. With utilities carrying smaller stockpiles and projections showing a growing reliance on coal for a majority of the nation's electricity production, any significant disruption to the transportation network has serious implications for the overall reliability of the grid as a whole.

Off-shore production is particularly susceptible to extreme weather events. Hurricane Ivan (2004) destroyed seven GOM platforms, significantly damaged 24 platforms, and damaged 102 pipelines (MMS 2006). Hurricanes Katrina and Rita in 2005 destroyed more than 100 platforms and damaged 558 pipelines (MMS 2006). The two photographs in Figure 3.4 show the

Figure 3.4 Hurricane damage in the Gulf of Mexico – Mars platform

Before Hurricane

After Hurricane

Mars deepwater platforms before and after the 2005 hurricanes. The $250 million Typhoon platform was so severely damaged that Chevron is working with the MMS to sink it as part of an artificial reef program in the GOM; the billion dollar plus Mars platform has been repaired and returned to production about 8 months post hurricane.

3.1.5 Adaptation to Extreme Events

Energy assets can be protected from these impacts both by protecting the facility or relocating it to safer areas. Hardening could include reinforcements to walls and roofs, the building of dikes to contain flooding, or structural improvements to transmission assets. However, the high cost of relocating or protecting energy infrastructure drives many companies to hedge these costs against potential repair costs if a disaster does strike. For example, it is currently estimated to cost up to $10 billion to build a new refinery from the ground up (Petroleum Institute for Continuing Education undated), compared with costs to fully harden a typical at-risk facility against a hurricane and with the few million dollars in repairs that may or may not be required if a hurricane does strike. Relocation of rail lines also faces a similar dilemma. BNSF's capacity additions in the Powder River Basin are expected to cost over $200 million dollars to add new track in a relatively flat region with low land prices; changes to rail lines in the Appalachian region would be many times more due to the difficult topography and higher land acquisition costs.

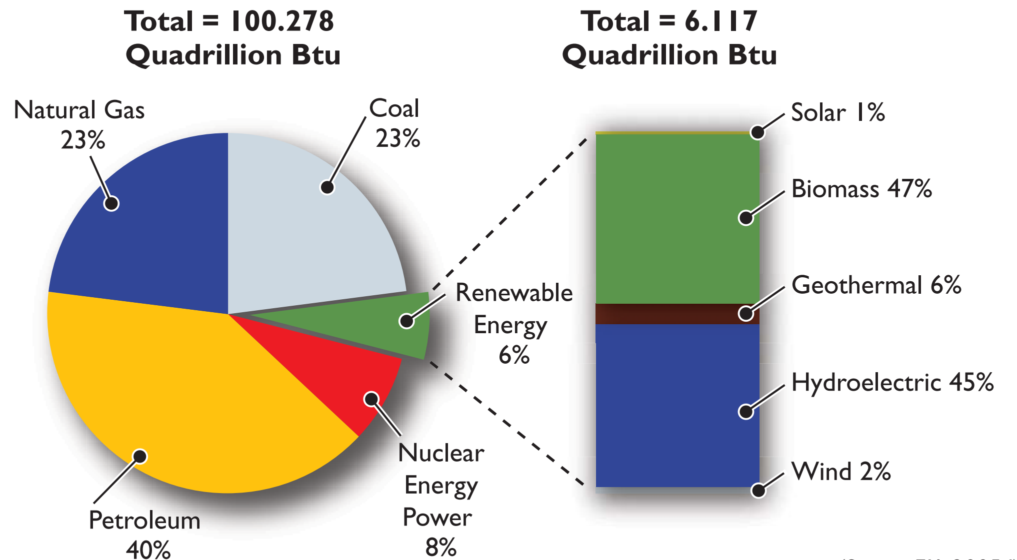
Industry, government agencies, and the American Petroleum Institute met jointly in March 2006 (API 2006a) to plan for future extreme weather events. Interim guidelines for jackup (shallow water) rigs (API 2006b) and for floating rigs (API 2006c) have been developed. MMS, DOT, and several industry participants have formed a Joint Industry Program (JIP) (Stress Subsea, Inc. 2005) to develop advanced capabilities to repair damaged undersea pipelines.

3.2 EFFECTS ON RENEWABLE ENERGY PRODUCTION

Renewable energy production accounted for about 6% of the total energy production in the United States in 2005 (Figure 3.5); biomass and hydropower are the most significant contributors (EIA 2005d), and the use of renewable energy is increasing rapidly in other sectors such as wind and solar. Biomass energy is primarily used for industrial process heating, with substantially increasing use for transportation fuels

Figure 3.5. Renewable Energy's Share In U.S. Energy Supply (2005)

(http://www.eia.doe.gov/cneaf/solar.renewables/page/trens/highlight1.html)



(Source: EIA 2005d)

and additional use for electricity generation. Hydropower is primarily used for generating electricity, providing 270 billion kWh in 2005 (EIA, 2005d). Wind power is the fastest growing renewable energy technology, with total generation increasing to 14 billion kWh in 2005 (EIA 2006). Because renewable energy depends directly on ambient natural resources such as hydrological resources, wind patterns and intensity, and solar radiation, it is likely to be more sensitive to climate variability than fossil or nuclear energy systems that rely on geological stores. Renewable energy systems are also vulnerable to damage from extreme weather events. At the same time, increasing renewable energy production is a primary means for reducing energy-related greenhouse gas emissions and thereby mitigating the impacts of potential climate change. Renewable energy sources are therefore connected with climate change in very complex ways: their use can affect the magnitude of climate change, while the magnitude of climate change can affect their prospects for use.

3.2.1 Hydroelectric Power

Hydropower is the largest renewable source of electricity in the United States. In the period 2000-2004, hydropower produced approximately 75% of the electricity from all renewable sources (EIA 2005d). In addition to being a major source of base-load electricity in some regions of the United States (e.g., Pacific Northwest states), hydropower plays an important role in stabilizing electrical transmission grids, meeting peak loads and regional reserve requirements for generation, and providing other ancillary electrical energy benefits that are not available from other renewables when storage is unavailable. Hydropower project design and operation is very diverse; projects vary from storage projects with large, multipurpose reservoirs to small run-of-river projects that have little or no active water storage. Approximately half of the U.S. hydropower capacity is federally owned and operated (e.g., Corps of Engineers, Bureau of Reclamation, and the Tennessee Valley Authority); the other half is at nonfederal projects that are regulated by the Federal Energy Regulatory Commission. Nonfederal hydropower projects outnumber federal projects by more than 10:1.

The interannual variability of hydropower generation in the United States is very high, especially relative to other energy sources (Figure 3.6). The difference between the most recent high (2003) and low (2001) generation years is 59 billion kWh, approximately equal to the total electricity from biomass sources and much more than the generation from all other non-hydropower renewables (EIA 2006). The amount of water available for hydroelectric power varies greatly from year to year, depending upon weather patterns and local hydrology, as well as on competing water uses, such as flood control, water supply, recreation, and instream flow requirements (e.g., conveyance to downstream water rights, navigation, and protection of fish

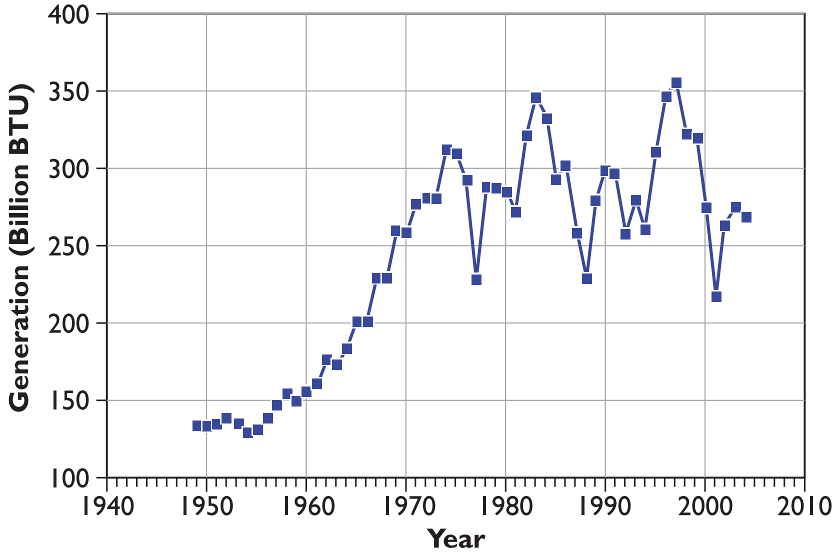


Figure 3.6. Historical Variability Of Total Annual Production Of Hydroelectricity From Conventional Projects In The U.S. (data from EIA Annual Energy Outlook, 2005).

and wildlife). The annual variability in hydropower is usually attributed to climate variability, but there are also important impacts from multiple use operational policies and regulatory compliance.

There have been a large number of published studies on the climate impacts on water resource management and hydropower production (e.g., Miller and Brock 1988; Lettenmaier et al. 1999; Barnett et al. 2004). Significant changes are being detected now in the flow regimes of many western rivers (Dettinger 2005) that are consistent with the predicted effects of global warming. The sensitivity of hydroelectric generation to both changes in precipitation and river discharge is high, in the range 1.0 and greater (e.g., sensitivity of 1.0 means 1% change in precipitation results in 1% change in generation). For example, Nash and Gleick (1993) estimated sensitivities up to 3.0 between hydropower generation and stream flow in the Colorado Basin (i.e., change in generation three times the change in stream flow). Such magnifying sensitivities, greater than 1.0, occur because water flows through multiple power plants in a river basin. Climate impacts on hydropower occur when either the total amount or the timing of runoff is altered, for example when natural water storage in snow pack and glaciers is reduced under hotter climates (e.g., melting of glaciers in Alaska and the Rocky Mountains of the U.S.). Projections that climate change is likely to reduce snow pack and associated runoff in the U.S. West are a matter of particular concern.

Hydropower operations are also affected indirectly when air temperatures, humidity, or wind patterns are affected by changes in climate, and these driving variables cause changes in water quality and reservoir dynamics. For example, warmer air temperatures and a more stagnant atmosphere cause more intense stratification of reservoirs behind dams and a depletion of dissolved oxygen in hypolimnetic waters (Meyer et al. 1999). Where hydropower dams have tailwaters supporting cold-water fisheries for trout or salmon, warming of reservoir releases may have unacceptable consequences and require changes in project operation that reduce power production.

Evaporation of water from the surface of reservoirs is another important part of the water cycle that may be will be affected by climate change and may lead to reduced water for hydropower. However, the effects of climate change on evaporation rates is not straight-forward. While evaporation generally increases with increased air or water temperatures, evaporation also depends on other meteorological conditions, such as advection rates, humidity, and solar radiation. For example, Ohmura and Wild (2002) described how observed evaporation rates decreased between 1950 and 1990, contrary to expectations associated with higher temperatures. Their explanation for the decrease was decreased solar radiation. Large reservoirs with large surface area, located in arid, sunny parts of the U.S., such as Lake Mead on the lower Colorado River (Westenburg et al., 2006), are the most likely places where evaporation will be greater under future climates and water availability will be less for all uses, including hydropower.

Competition for available water resources is another mechanism for indirect impacts of climate change on hydropower. These impacts can have far-reaching consequences through the energy and economic sectors, as happened in the 2000-2001 energy crises in California (Sweeney, 2002).

Recent stochastic modeling advances in California and elsewhere are showing how hydropower systems may be able to adapt to climate variability by reexamining management policies (Vicuña et al., 2006). The ability of river basins to adapt is proportional to the total active storage in surface water reservoirs (e.g., Aspen Environmental Group and M-Cubed, 2005). Adaptation to potential future climate variability has both near-term and long-term benefits in stabilizing water supplies and energy production (e.g., Georgakakos et al., 2005), but water management institutions are generally slow to take action on such opportunities (Chapter 4).

3.2.2 Biomass Power and Fuels

Total biomass energy production has surpassed hydroelectric energy for most years since 2000 as the largest U.S. source of total renewable energy, providing 47% of renewable or 4% of total U.S. energy in 2005 (EIA, 2006). The largest source of that biomass energy (29%) was black liquor from the pulp and paper industry combusted as part of a process to recover pulping chemicals to provide process heat as well as generating electricity. Wood and wood waste from sources such as lumber mills provide more than 19% (industrial sector alone) and combusted municipal solid waste and recovered landfill gas provide about 16%, respectively, of current U.S. biomass energy (EIA, 2005d). Because energy resource generation is a byproduct of other activities in all these cases, direct impacts of climate change on these or most other sources of biomass power production derived from a waste stream may be limited unless there are significant changes in forest or agricultural productivity that are a source of the waste stream. There are few examples of literature addressing this area, though Edwards notes that climate-change-induced events such as timber die-offs could present a short-term opportunity or a long-term loss for California (Edwards, 1991).

Liquid fuel production from biomass is highly visible as a key renewable alternative to imported oil. Current U.S. production is based largely on corn for ethanol and, to a lesser extent, soybeans for biodiesel. In the longer term, cellulosic feedstocks may supplant grain and oilseed crops for transportation fuel production from biomass. Cellulosic crop residues such as corn stover and wheat straw would likely be affected by climate change the same way as the crops themselves due to a rise in average temperatures, more extreme heat days, and changes in precipitation patterns and timing, with greater impact on fuel production because that would be their primary use. Potential dedicated cellulosic energy crops for biomass fuel, such as grasses and fast-growing trees, would also be directly affected by climate change. As discussed below, limited literature suggests that for at least one region, one primary energy crop candidate—switchgrass—may benefit from climate change, both from increased temperature and increased atmospheric carbon dioxide levels.

Approximately 10% of U.S. biomass energy production (EIA, 2005d), enough to provide about 2% of U.S. transportation motor fuel (Federal Highway Administration, 2003), currently comes from ethanol made predominantly from corn grown in the Midwest (Iowa, Illinois, Nebraska, Minnesota, and South Dakota are the largest ethanol producers). Climate change sufficient to substantially affect corn production would likely impact the resource base, although production and price effects in the longer term are unclear. Production of biodiesel from soybeans—growing rapidly, but still very small—is likely a similar situation. In the long term, however, significant crop changes—and trade-offs between them as they are generally rotated with each other—would likely have an impact in the future. Looking at Missouri, Iowa, Nebraska, and Kansas, with an eye toward energy production, Brown et al., 2000 used a combination of the NCAR climate change scenario, regional climate, and crop productivity models to predict how corn, sorghum, and winter wheat (potential ethanol crops) and soybeans (biodiesel crop) would do under anticipated climate change. Negative impacts from increased temperature, positive impacts from increased precipitation, and positive impacts from increased atmospheric carbon dioxide combined to yield minimal negative change under modest carbon dioxide level increases but 5% to 12% yield increases with high carbon dioxide level increases. This assessment did not, however, account for potential impact of extreme weather events – particularly the frequency and intensity of events involving hail or prolonged droughts – that may also negatively impact energy crop production.

Although ethanol production from corn can still increase substantially (mandated to double under the recently enacted renewable fuel standard), it can still only meet a small portion of the need for renewable liquid transportation fuels to displace gasoline if dependence on petroleum imports is to be reduced. Processing the entire projected 2015 corn crop to ethanol (highly unrealistic, of course) would only yield about 35 billion gallons of ethanol, less than 14% of the gasoline energy demand projected for that year. Biomass fuel experts are counting on cellulosic biomass as the feedstock to make larger scale renewable fuel production possible. A recent joint study by the U.S. Departments of Agriculture and Energy (USDA and DOE), *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, projected that by 2030, enough biomass could be made available to meet 40% of 2004 gasoline demand via cellulosic ethanol production and other technologies. The two largest feedstocks identified are annual crop residues and perennial dedicated energy crops (NREL, 2006).

The primary potential annual crop residues are corn stover—the leaves, stalks, and husks generally now left in the field—and wheat straw. Corn stover is the current DOE research focus in part because it is a residue with no incremental cost to grow and modest cost to harvest, but also particularly because of its potential large volume. Stover volume is roughly equivalent to grain volume, and corn is the largest U.S. agricultural crop. As such, it would be affected by climate change in much the same way as the corn crop itself, as described above.

Frequently discussed potential dedicated perennial energy crops include fast-growing trees such as hybrid poplars and willows and grasses such as switchgrass (ORNL, 2006) Switchgrass is particularly attractive because of its large regional adaptability, fast growth rate, minimal adverse environmental impact, and ease of harvesting with conventional farm equipment. The primary objective of the Brown et al. , 2000 study referenced above for Missouri, Iowa, Nebraska, and Kansas was to see how climate change would affect growth of switchgrass. The study projected that switchgrass may benefit from both higher temperatures (unlike the grain crops) and higher atmospheric carbon dioxide levels, with yield increasing 74% with the modest CO_2 increase and nearly doubling with the higher CO_2 increase. Care should be taken in drawing definitive conclusions, however, from this one study. One may not expect the projected impact to be as beneficial for southern regions already warm enough for rapid switchgrass growth or more northern areas still colder than optimal even with climate change, but this analysis has not yet been conducted.

3.2.3 Wind Energy

Wind energy currently accounts for about 2.5% of U.S. renewable energy generation, but its use is growing rapidly, and it has tremendous potential due to its cost-competitiveness with fossil fuel plants for utility-scale generation and its environmental benefits. In addition, wind energy does not use or consume water to generate electricity. Unlike thermoelectric and fossil fuel generation that is inextricably linked to the availability of adequate, sustainable water supplies, wind energy can offer communities in water-stressed areas the option of economically meeting increasing energy needs without increasing demands on valuable water resources.

Although wind energy will not be impacted by changing water supplies like the other fuel sources, projected climate change impacts--such as changes in seasonal wind patterns or strength--would likely have significant positive or negative impacts because wind energy generation is a function of the cube of the wind speed. One of the barriers slowing wind energy development today is the integration of a variable resource with the utility grid. Increased variability in wind patterns could create additional challenges for accurate wind forecasting for generation and dispatch planning and for the siting of new wind farms.

In addition to available wind resources, state and federal policy incentives have played a key role in the growth of wind energy. Texas currently produces the most wind power, followed by California, Iowa, Minnesota, Oklahoma, and Oregon (AWEA, **www.awea.org/projects**, 2006). These regions are expected to continue to be among the leading wind-power areas in the near term. Although North Dakota and South Dakota have modest wind development, they also have tremendous wind potential, particularly if expanded transmission capacity allows for development of sites further from major load centers.

The siting of utility-scale wind generation is highly dependent on proximity and access to the grid and the local wind speed regime. Changes in wind patterns and intensity due to climate change could have an effect on wind energy production at existing sites and planning for future development, depending on the rate and scale of that change. One study modeled wind speed change for the United States, divided into northern and southern regions under two climate-change circulation models. Overall, the Hadley Center model suggested minimal decrease in average wind speed, but the Canadian model predicted very significant decreases of 10%–15% (30%–40% decrease in power generation) by 2095. Decreases were most pronounced after 2050 in the fall for both regions and in the summer for the northern region (Breslow and Sailor, 2002).

Another study mapped wind power changes in 2050 based on the Hadley Center General Circulation Model—the one suggesting more modest change of the two used by Breslow and Sailor above. For most of the United States, this study predicted decreased wind resources by as much as 10% on an annual basis and 30% on a seasonal basis. Wind power increased for the Texas-Oklahoma region and for the Northern California-Oregon-Washington region, although the latter had decreased power in the summer. For the Northern Great Plains and for the mountainous West, however, the authors predicted decreased wind power (Segal et al. 2001). Edwards suggests that warming-induced offshore current changes could intensify summer winds for California and thus increase its wind energy potential (Edwards, 1991). Changes in diurnal wind patterns could also have a significant impact on matching of wind power production with daily load demands.

3.2.4 Solar Energy

Photovoltaic (PV) electricity generation and solar water heating are suitable for much of the United States, with current deployment primarily in off-grid locations and rooftop systems where state or local tax incentives and utility incentives are present. Utility-scale generation is most attractive in the Southwest with its high direct-radiation resource, where concentrating high-efficiency PV and solar thermal generation systems can be used. California and Arizona currently have the only existing utility-scale systems (EIA, 2005d) with additional projects being developed in Colorado, Nevada, and Arizona.

Pan et al. 2004 modeled changes to global solar radiation through the 2040s based on the Hadley Center circulation model. This study projects a solar resource reduced by as much as 20% seasonally, presumably from increased cloud cover throughout the country, but particularly in the West with its greater present resource. Increased temperature can also reduce the effectiveness of PV electrical generation and solar thermal energy collection. One international study predicts that a 2% decrease in global solar radiation will decrease solar cell output by 6% overall (Fidje and Martinsen, 2006). Anthropogenic sources of aerosols can also decrease average solar radiation, especially on a regional or localized basis. The relationship between the climate forcing effect of greenhouse gases and aerosols is complex and an area of extensive research. This field would also benefit from further analysis on the nexus between anthropogenic aerosols, climate change, solar radiation, and impacts on solar energy production.

3.2.5 Other Renewable Energy Sources

Climate change could affect geothermal energy production [6% of current U.S. renewable energy (EIA, 2005d) and concentrating solar power Rankine cycle power plants] in the same way that higher temperatures reduce the efficiency of fossil-fuel-boiler electric turbines, but there is no recent research on other potential impacts in this sector due to climate change. For a typical air-cooled binary cycle geothermal plant with a 330°F resource, power output will decrease about 1% for each 1°F rise in air temperature.

The United States currently does not make significant use of wave, tidal, or ocean thermal energy, but each of these could be affected by climate change due to changes in average water temperature, temperature gradients, salinity, sea level, wind patterns affecting wave production, and intensity and frequency of extreme weather events. Harrison observes that wave heights in the North Atlantic have been increasing and discusses how wave energy is affected by changes in wind speed (Harrison and Wallace, 2005), but very little existing research has been identified that directly addresses the potential impact of climate change on energy production from wave, tidal, or ocean thermal technologies.

3.2.6 Summary

Of the two largest U.S. renewable energy sources, hydroelectric power generation can be expected to be directly and significantly affected by climate change, while biomass power and fuel production impacts are less certain in the short term. The impact on hydroelectric production will vary by region, with potential for production decreases in key areas such as the Columbia River Basin and Northern California. Current U.S. electricity production from wind and solar energy is modest but anticipated to play a significant role in the future as the use of these technologies increases. As such, even modest impacts in key resource areas could substantially impact the cost competitiveness of these technologies due to changes in electricity production and impede the planning and financing of new wind and solar projects due to increased variability of the resource. Renewable energy production is highly susceptible to localized and regional changes in the resource base. As a result, the greater uncertainties on regional impacts under current climate change modeling pose a significant challenge in evaluating medium to long-term impacts on renewable energy production.

3.3 EFFECTS ON ENERGY TRANSMISSION, DISTRIBUTION, AND SYSTEM INFRASTRUCTURE

In addition to the direct effects on operating facilities themselves, networks for transport, electric transmission, and delivery would be susceptible to changes due to climate change in stream flow, annual precipitation and seasonal patterns, storm severity, and even temperature increases (e.g., pipelines handling supercritical fluids may be impacted by greater heat loads if temperatures increase and/or cloud cover diminishes).

3.3.1 Electricity Transmission and Distribution

Severe weather events and associated flooding can cause direct disruptions in energy services. With more intense events, increased disruptions might be expected. Electricity reliability might also be affected as a result of increased demand combined with high soil temperatures and soil dryness (IPCC, 2001a). Figure 3.7 illustrates the major grid outage that was initiated by a lightning strike, as one example.

Grid technologies in use today are at least 50 years old and, although "smart grid" technologies exist, they are not often employed. Two such technologies that may be employed to help offset climate impacts include upgrading the grid by employing advanced conductors that are capable of withstanding greater temperature extremes and automation of electricity distribution (Gellings and Yeager, 2004).

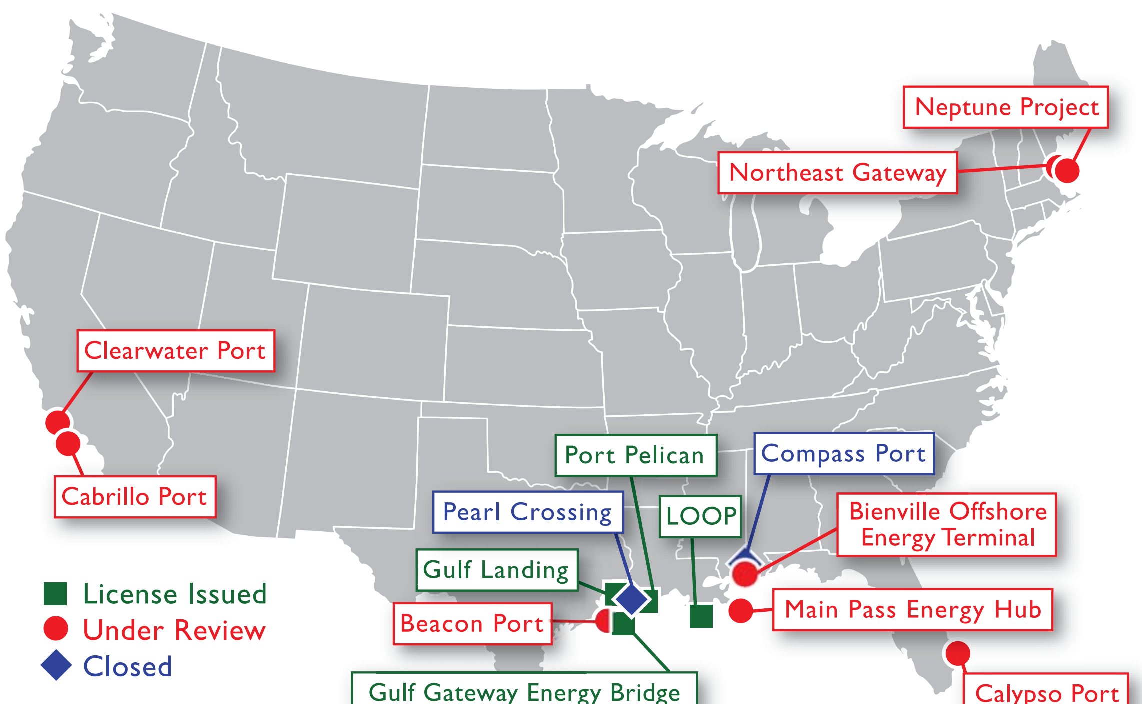
3.3.2 Energy Resource Infrastructure

A substantial part of the oil imported into the United States is transported over long distances from the Middle East and Africa in supertankers. While these supertankers are able to of-

Figure 3.7. Approximate Area of Blackout of 2003 In The United States. *Source: NETL*

flood within the ports of other countries, they are too deeply drafted to enter the shallow U.S. ports and waters. This occurs because, unlike most other countries, the continental shelf area of the eastern United States extends many miles beyond its shores and territorial waters. This leads to a number of problems related to operation of existing ports, and to programs (such as NOAA's P.O.R.T.S. Program) to improve efficiency at these ports. In addition, the Deepwater Ports Act, 1975, has led to plans to develop a number of deepwater ports either for petro-

Figure 3.8. Proposed Deepwater Ports For Petroleum And LNG. *(Source: U.S. Maritime Administration)*



leum or LNG import. These planned facilities are concentrated in relatively few locations, in particular with a concentration along the Gulf Coast (Figure 3.8). Changes in weather patterns, leading to changes in stream flows and wind speed and direction can impact operability of existing harbors. Severe weather events can impact access to deepwater facilities or might disrupt well-established navigation channels in ports where keel clearance is a concern (DOC/DOE, 2001).

Climate change may also affect the performance of the extensive pipeline system in the United States. For example, for CO_2-enhanced oil recovery, experience has shown that summer injectivity of CO_2 is about 15% less than winter injectivity into the same reservoir. The CO_2 gas temperature in Kinder Morgan pipelines during the winter is about 60°F and in late summer about 74oF. At higher temperatures, compressors and fan coolers are less efficient and are processing a warmer gas. Operators cannot pull as much gas off the supply line with the given horsepower when the CO_2 gas is warm (Source: personal communication from K. Havens of Kinder Morgan CO_2).

Efficiencies of most gas injection are similar, and thus major gas injection projects like produced gas injection on the North Slope of Alaska have much higher gas injection and oil production during cold winter months. Persistently higher temperatures would have an impact on deliverability and injectivity for applications where the pipeline is exposed to ambient temperatures.

3.3.3 Storage and Landing Facilities

Strategic Petroleum Reserve storage locations (EIA 2004b) that are all along the Gulf Coast were selected because they provide the most flexible means for connecting to the commercial oil transport network. Figure 3.9 illustrates their locations along the Gulf Coast in areas USGS 2000 sees as being susceptible to sea-level rise, as well as severe weather events. Similarly located on the Sabine Pass is the Henry Hub, the largest gas transmission interconnection site in the U.S., connecting 14 interstate and intrastate gas transmission pipelines. Henry Hub was out of service briefly from Hurricane Katrina and for some weeks from Hurricane Rita, which made landfall at Sabine Pass.

3.3.4 Infrastructure Planning And Considerations For New Power Plant Siting

Water availability and access to coal delivery are currently critical issues in the siting of new coal-fired generation capacity. New capacity, except on coasts and large estuaries, will generally require cooling towers rather than once-through cooling water usage based on current and expected regulations (EPA, 2000) independent of climate change issues. New turbine capacity will also need to be designed to respond to the new ambient conditions.

Siting of new nuclear units will face the same water availability issues as large new coal-fired units; they will not need to deal with coal deliverability but may depend on barge transport to allow factory fabrication rather than site fabrication of large, heavy wall vessels, as well as for transportation of any wastes that need to be stored off-site.

Capacity additions and system reliability have recently become important areas for discussion. A number of approaches are being considered, such as to run auctions (or other approaches) to stimulate interest in adding new capacity, such as efforts by FERC to encourage capacity investments through regional independent system operator (ISO) organizations, without sending signals that would result in overbuilding (as has happened in the past). Planning to ensure that both predictions of needed capacity and mechanisms for stimulating companies to build such capacity (while working through the process required to announce, design, permit, and build it) will become more important as future demand is affected by climatic shifts. Similarly, site selection may need to factor in longer-term climatic changes for technologies as long-lived as coal-fired power plants (which may last for 50 - 75 years) (NARUC, 2006).

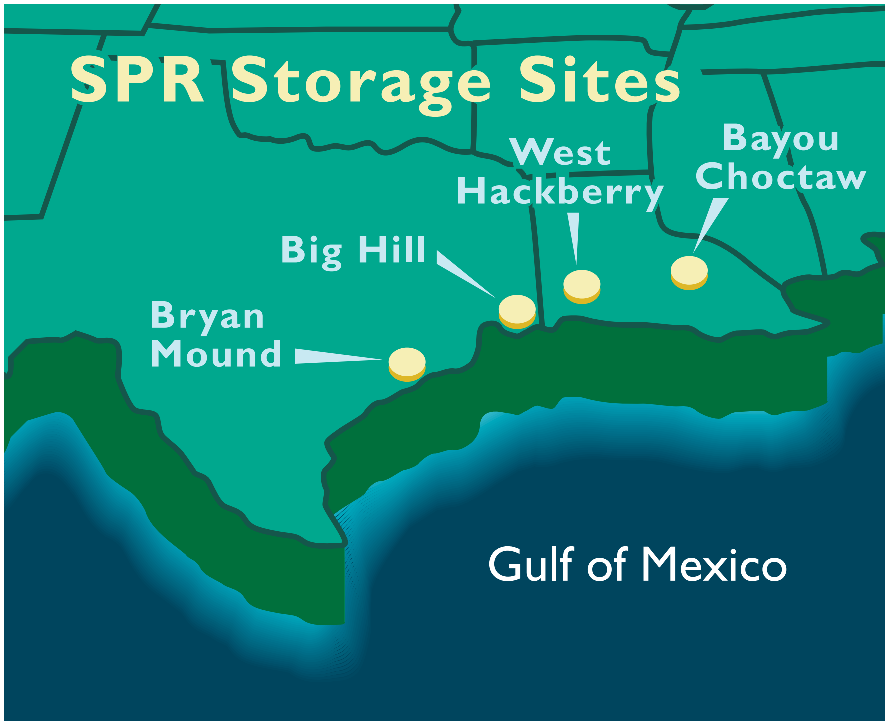


Figure 3.9. Strategic Petroleum Reserve Storage Sites *(Source: NETL)*

3.4 SUMMARY OF KNOWLEDGE ABOUT POSSIBLE EFFECTS

Significant uncertainty exists about the potential impacts of climate change on energy production and distribution, in part because the timing and magnitude of climate impacts are uncertain. This report summarizes many of the key issues and provides information available on possible impacts; however this topic represents a key area for further analysis.

Many of the technologies needed for existing energy facilities to adapt to increased temperatures and decreased water availability are available for deployment; and, although decreased efficiencies and lower output can be expected, significant disruptions seem unlikely. Incorporating potential climate impacts into the planning process for new facilities will strengthen the infrastructure. This is especially important for water resources, as electricity generation is one of many competing applications for what may be a (more) limited resource.

There are regionally important differences in adaptation needs. This is true for the spectrum of climate impacts from water availability to increased temperatures and changing patterns of severe weather events. The most salient example is for oil and gas exploration and production in Alaska, where projected temperature increases may be double the global average, and melting permafrost and changing shorelines could significantly alter the landscape and available opportunities for oil and gas production

Increased temperatures will also increase demand-side use, and the potential system-wide impacts on electricity transmission and distribution and other energy system needs are not well understood. Future planning for energy production and distribution may therefore need to accommodate possible impacts