In the Midwest study (Todd, et al. 2006) for sites with long historical records, the 24-hour 100-year recurrence interval rainfall depth increased at 89 % of the study locations, with little change for the higher frequency storms with 2- and 10-year event return periods. Design standards for most common drainage structures are typically based upon the intensity-depth-duration characteristics of extreme storm events with recurrence intervals computed by extreme-value probability distributions: this implies an assumption of *climatic stationarity* (See Sections 2 and 3 for further discussion). In 2004 the National Oceanic and Atmospheric Administration (NOAA) released the Precipitation-Frequency Atlas of the United States, the Atlas 14 (Bonnin et al. 2004). This publication updated the point precipitation frequency estimates for much of the eastern and southwestern parts of the United States. The standard precipitation frequency atlas for the eastern U.S. had been the National Weather Bureau Technical Paper No. 40 (TP-40) (Hershfield, 1961), based upon precipitation data collected up to 1957 with an average of 15 data years.

The Atlas 14 data are considered more suitable for hydraulic design and water resource planning than the TP-40 estimates, since precipitation values are available for the actual sites rather than interpolated values obtained from the TP-40 isohyetal maps. Todd et al. (2006) compared point rainfall data obtained from TP-40 and NOAA Atlas 14 for sites with over 100 years of precipitation records in Illinois, Indiana, Kentucky and Ohio. In the four-state study region, 100-year recurrence interval events generally increased in magnitude from the TP-40 estimates to the NOAA Atlas 14 precipitation depths. All four states had an average increase for the 100-year, 1-hour, 6-hour, 12-hour and 24-hour duration events. Todd et al. (2006) state that communities in the United States that continue to use the TP-40 data (which has been shown to underestimate the precipitation depth for low-frequency, high-magnitude events in this four-state region) should reevaluate their reliance upon this data source in hydraulic analysis and design. Otherwise, use of these dated precipitation statistics could lead to inadequate erosion control and undersized reservoirs, storm sewers, culverts and other drainage and water storage structures—all of which could cause increased flooding.

Deterministic dynamic, physically based rainfall-runoff distributed routing models, such as the U.S. EPA Stormwater Management Model (Huber and Dickinson, 1988; Rossman, 2010), mathematically describe the transformation of precipitation into surface runoff: from rainfall input to subsurface infiltration or generation of overland flow, and then flow into the man-made drainage system. Among the many variables that describe these processes mathematically are the width, area, percent imperviousness, ground slope, roughness parameters of the land cover for both impervious and pervious fractions, and several infiltration rate parameters that depend upon methods chosen.

*Recommendations needed for longer-term improvements of practices.* The improvements of practices described in the following subsection will take several years for consensus procedures to be implemented. Meanwhile, a rainfall-runoff model, calibrated against measured data, is an excellent planning and design tool, as it is dependent upon a carefully selected precipitation input, whether it is a discrete design storm event or a long-term time series of recorded precipitation events. Guidance for practitioners is needed in order to select the most appropriate methodology for choosing such precipitation inputs.

Given the expected changes in our climate, there is a need to account for uncertainty and variability and to replace standards and practices that were once considered permanent with ones that account for climatic nonstationarity. The primary means of projecting future climate are GCMs, but they are not well suited to simulate temperatures and precipitation over relatively small geographic areas and timescales. Table 2.1 in Section 2 provides an informative summary of changes that may affect engineering at global scales. As noted in Section 3, we must consider how to effectively use climate information to revise design standards. There will be a tradeoff between designing for larger uncertain events and project cost. Thus, decisions about our infrastructure and long-range water resource planning must provide flexibility and viable options, such as:

- designing control systems conservatively to account for potential future increases in rainfall intensities;
- maximizing the infiltration of runoff to the subsurface;
- protecting existing wetlands and constructing more wetlands to hold runoff and recharge groundwater;
- improving the performance of existing systems through enhanced monitoring and improving single-event and multiple-event modeling and feedback;
- updating rainfall statistics frequently and simulate future scenarios accordingly, and;
- implementing real-time internet-based information systems.

In terms of stormwater management, low impact development (LID) runoff control methods or more complex structural Best Management Practices (BMPs) may provide the resiliency required for adaptation implementation. Among the LID methods are the installation of rain barrels, porous pavement, infiltration trenches, vegetative swales and bio-retention cells. Much more efficient structural BMPs are engineered systems and methods designed to provide temporary storage and treatment of stormwater runoff for the removal of pollutants (Muthukrishnan et al, 2004). These include the installation of wet and dry detention ponds, retention ponds and constructed wetlands, as noted earlier. Wetlands in the U.S. are estimated to provide $23.2 billion in storm protection (Foster et al. 2011).

The urbanization of an area alters the local water balance. Often overlooked is the potential interaction with subsurface components, such as groundwater levels, flow and contaminant exchanges. Stormwater management also requires knowledge and understanding of the groundwater and surface water interactions prior to finalizing development; this is particularly critical if constructed wetlands are to be considered a stormwater control and treatment BMP option. The large surface area requirement of constructed wetlands helps to minimize the "extreme" water level fluctuations during all but the larger storm events. The development of a comprehensive wetland model that has both surface flow and solute transport components was presented by Kazezyilmaz-Alhan, et al. (2007). Their model incorporates surface/ground water interactions and accounts for upstream contributions from urbanized areas (see Figure 4.2). The time series of flows and contaminants predicted by a calibrated distributed routing rainfall-runoff model (subjected to an annual time series of 15-minute rainfall) constitutes the upstream component of the wetland model. The occurrence of future extreme climatic events resulting in elongated and more frequent flooding and drought, water quantity shortages, sporadic and uncharacteristic rainfall patterns, increases in high intensity rainfall events, and higher possibility for impaired water quality suggests a probabilistic approach that accounts for uncertainty. The one common theme between nearly all studies related to drought and flood modeling is the use of extreme value theory (EVT) to adequately model these phenomena.

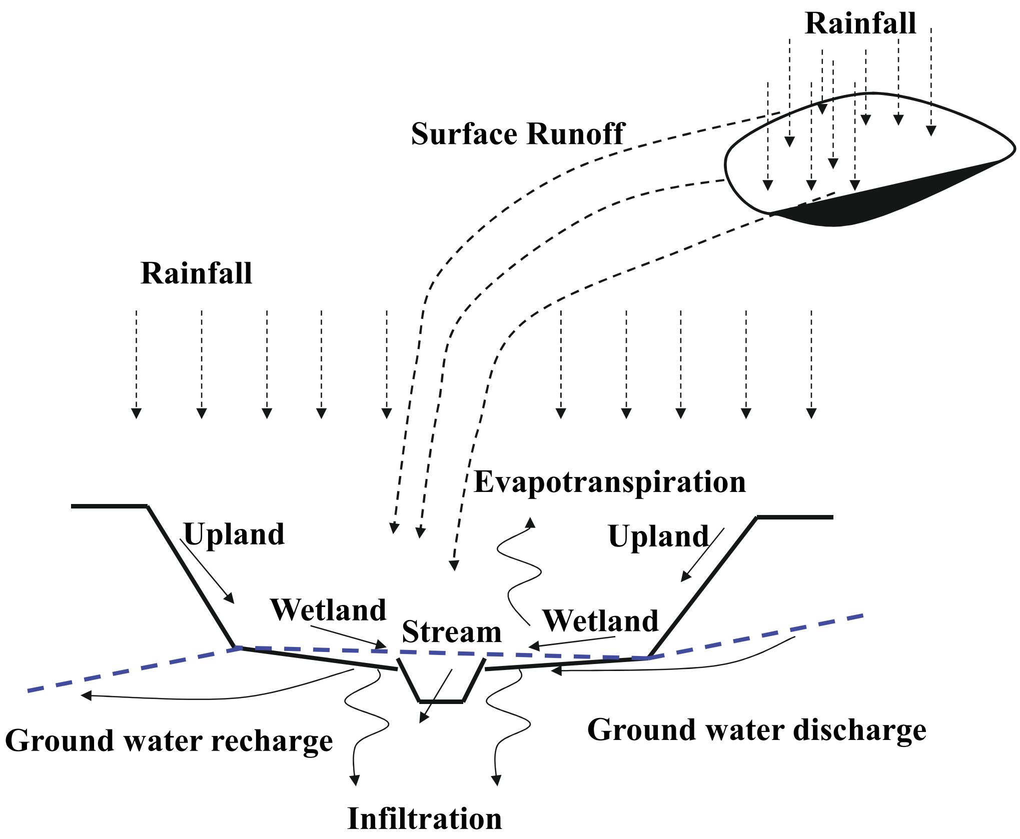


Figure 4.2: Surface/Ground Water Interactions in a Constructed Wetland
Source: Modified from Kazezyilmaz-Alhan, et al. (2007).

A thorough review of stormwater infrastructure design practices is required. The techniques used for developing design storms are quite dated, many of which are based on either rainfall inputs from Technical Paper No. 40 (TP-40) (Hershfield, 1961) for precipitation data collected up to 1957 or Intensity Duration Frequency curves developed assuming Gumbel extreme value distributions.

Thorough evaluations of concurrent rainfall and streamflow records are needed, which perhaps can be accommodated by splitting the available records into large time series, say, first 40 years compared to next 40 years, etc., and comparing the statistical differences. The results from applying both design storms and more modern computational methods would be elucidating. This type of analysis would set a baseline for use of climate change simulation models.

### *4.5 Coastal management*

*Scope of the sector and its major engineering practices.* When it comes to climate change, flooding and erosion are the primary concerns regarding civil engineering works. As well, adjustments of habitat boundaries in response to changing water level, temperature and salinity are also important considerations. Coastal flooding and erosion risks follow changing frequency, intensity and paths of storms at sea, superimposed on eustatic sea-level rise caused by melting of land ice and ocean thermal expansion. Erosion is also influenced by changes induced by climate change in prevailing coastal winds and by sediment budgets modified by new hydrological patterns of coastal watersheds. Some coastal areas suffer long-term land subsidence. Arctic coastal flooding and erosion problems are made worse by sea ice retreat with diminished ice dampening of winter waves and by thaw settlement of coastal permafrost.

The challenges engineers encounter to develop design criteria for coastal works in a warming world are similar to those for inland water resource developments. Determination of changing probabilities for extreme storm surge using GCMs are not yet reliable. Variable nearshore bathymetry, changed by erosion and new sediment transport patterns, is not addressed in these simulations. Historical trends of shoreline change are useful, especially if they can resolve recent accelerations. Storm surge and erosion risk assessments based on numerical modeling of historical wave generation and propagation (hind-casting) and site-specific measurements remain essential components of well-founded coastal engineering designs.

Design criteria for prevention of damage from coastal flooding to community infrastructure in the United States often follow guidance of FEMA (FEMA 2011). FEMA guidance also addresses design criteria for strong winds that accompany a surge during a storm at the coast, with particular focus on wind, wave and water levels with 1 % joint probability to be exceeded in any year (i.e., the 100-year return period). FEMA criteria are important because they are associated with the National Flood Insurance Program (NFIP). Communities have invested in studies to delineate zones with coastal hazards, as defined by FEMA for the NFIP. The extent of a hazard zone is not stationary in a changing climate. The last 100 years will not have the same statistical characteristics at a particular site as the next 100 years. Changes wrought by global climate change may only begin to be reflected in the last 10 years of measurements, but projections based on so short a record have poor confidence at the level of 100-year return period. FEMA climate change policy (FEMA 2012) promotes additional climate change judgments to define coastal flooding and erosion risks, but does not specify data sources or analytical procedures.

Corps of Engineers guidance for projects intended to prevent or mitigate coastal flooding and erosion damages to property is found in the Coastal Engineering Manual (CEM) (USACE, 2008). CEM guidance discusses alternative responses, including non-structural options, but focuses on structural design concepts and analyses. The CEM is the most widely used technical guidance for coastal engineers in the U.S., but does not provide advice for addressing climate change. The Corps of Engineers does have an Engineer Regulation (USACE, 2013) that requires all coastal activities by the agency to address the impacts from 3 different local sea-level change scenarios, the historical trend, an intermediate projected rise, and a worst-case projected rise.

### *4.6 Energy supply*

*Scope of the sector.* The U.S. energy supply system broadly consists of the infrastructure and fuels needed to supply the economy with electricity, energy for mobility (through refined oil products), industrial feedstock and heat. Figure 4.3 shows the various fuels that provided approximately 97.5 quadrillion BTUs (about 103 exajoules) of energy to the U.S in 2013. Energy fuels have specific uses in the economy, with about 28 % of U.S. primary energy used for transportation, 22 % for industry, 11 % for homes and businesses, and the remaining 39 % used to make electricity consumed by homes, businesses and industry (EIA, 2014). There are different levels of fungibility and therefore, different levels of resiliency to disruption between the sources and uses of U.S. energy. For example, transportation energy is overwhelmingly provided by petroleum products, while electricity is provided from a range of fuels.

The energy supply chain largely consists of the production and distribution of fuels and electricity, enabled via multiple and oftentimes interdependent infrastructure. Fuels for energy such as coal, natural gas and oil are extracted, and biomass relies on agricultural production. These fuels are often processed after extraction and then transported via rail and barge (coal, biomass, oil) or pipeline (natural gas and oil). Oil and biomass are then refined into liquid fuels and distributed by pipelines and trucks to end users, predominately in the transportation sector. Natural gas is distributed by pipeline to residential, commercial and industrial users for heating and industrial inputs. Coal and natural gas are delivered to electric power plants to create electricity, which is then delivered to customers through a vast electricity transmission and distribution network.

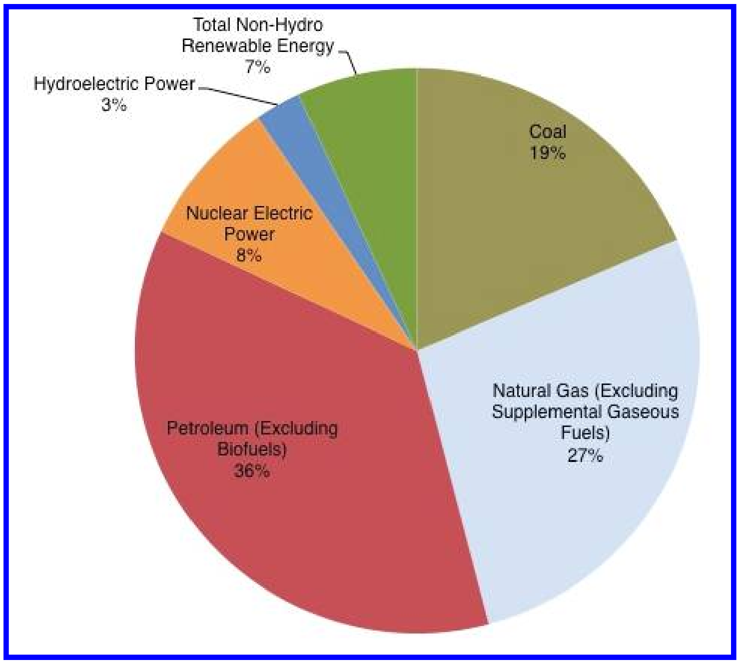


Figure 4.3: 2013 U.S. Primary Energy Consumption by Source.
Source: Data from EIA (2014).

Several different federal entities have oversight and regulatory authority over U.S. energy infrastructure, including the Department of Energy, the Environmental Protection Agency, the Federal Energy Regulatory Commission, the Nuclear Regulatory Commission, the North American Electric Reliability Commission, and the Department of Transportation (GAO, 2014). Other stakeholders include state and local regulatory bodies and private firms that design, construct, own, operate and maintain a large portion of the U.S. energy supply infrastructure. Table 4.1 highlights some of the major enabling infrastructure systems in the U.S. energy supply chain, many of which are traditionally associated with transportation infrastructure.

*Principal climate change impacts and vulnerabilities*. Across all regions and to varying degrees, the infrastructure supporting U.S. energy supply is currently impacted by climate change, and these impacts will amplify in the future. The Third National Climate Assessment of the U.S. Global Change Research Program state that: infrastructure is being damaged by sea-level rise, heavy downpours and extreme heat; damages are projected to increase with continued climate change, and; disruption in one infrastructure system can cascade to others (Melillo et al. 2014).

Under a changing climate, the frequency and intensity of some extreme weather events are expected to change, higher temperatures are expected increase electricity demands, water availability will constrain energy production, and sea level rise and storm surges can affect coastal energy infrastructure (Dell et al. 2014). The National Climate Assessment summarized some of the key regional climate indicators affecting the U.S. energy supply, shown in Table 4.2.

Table 4.1: Some of the Enabling Infrastructure for the U.S. Energy Supply Chain

| *Fuel Production* | *Fuel Transportation* | *Fuel Refining and Distribution* | *Electricity Production* | *Electricity Transmission and Distribution* |
|---|---|---|---|---|
| Oil, gas and coal extraction, processing and storage<br>Agricultural production of corn and other biomass | Oil, gas and liquids transmission pipelines<br>Natural gas compression stations<br>Bulk rail and barge transportation of coal, biomass and liquids<br>Fuel commodity import and export terminals | Petroleum and biomass refineries<br>Petroleum product storage<br>Roadway network for fuel distribution<br>City pipelines for natural gas distribution<br>Liquid fuel terminals and points of sale | Thermal power plants for coal, natural gas, nuclear, geothermal, biomass, and solar thermal generation<br>Dams and pumped hydroelectric generation<br>Wind and solar photovoltaic plants<br>Primary and emergency petroleum-fired generators | High voltage transmission lines<br>Transmission level substations<br>Distribution level substations<br>Medium voltage feeder lines<br>Residential, commercial and industrial voltage supply<br>Load control, dispatch facilities, and metering<br>Maintenance support facilities |

*Note:* These are a sample of the main types of energy supply infrastructure; additional enabling infrastructure not listed.

Table 4.2: Projected U.S. Regional Indicators from the 2014 National Climate Assessment

| *Key Indicator* | *Mean Annual Temperature (2071-2099 vs. 1971-2000)* | *Summer Precipitation (2071-2099 vs. 1971-2000)* | *Sea level Rise (2100)* | *Number of Days > 95 °F (2041-2070 vs. 1971-2000)* | *Number of Days < 10 °F (2041-2070 vs. 1971-2000)* |
|---|---|---|---|---|---|
| Northeast | +4°F to 9°F | -5% to +6% | 1.6 – 3.9 feet (0.5 – 1.2 m) | +10 days | -12 days |
| Southeast | +3°F to 8°F | -22% to +10% | | +23 days | -2 days |
| Midwest | +4°F to 10°F | -22% to +7% | | +14 days | -14 days |
| Great Plains | +3°F to 9°F | -27% to +5% | | +22 days | -4 days |
| Southwest | +4°F to 9°F | -13% to 3% | | +20 days | -3 days |
| Northwest | +3°F to 8°F | -34% to -4% | | +5 days | -7 days |

*Source:* Adapted from Dell et al. (2014), Tables 4.1 and 4.3. This source excludes extreme weather events. Sea-level rise will vary by geography and does not apply to the Midwest. Alaska, Hawaii and Pacific Islands were not studied.

*Impacts of increased frequency or severity of weather*. Energy infrastructure will be affected by an increase in the frequency and severity of extreme weather events, which have begun to occur across most of the U.S. The projected changes could include more frequent and intense precipitation, wildfire and drought (Dell et al. 2014). Increased storm intensity, coupled with sea-level rise and storm surge, could affect coastal oil and gas extraction, as well as transport and storage infrastructure. Barges utilize inland waterways and rail transportation often follows riverbeds. Therefore, increased river flooding could disrupt the supply of coal, petroleum products and other liquids, or biomass transported by both train and barge (Dell et al. 2014; DOE, 2013). Increased storms and river flooding could also threaten inland thermoelectric and hydroelectric generation facilities by damaging structural components, sediment deposition and flooded facilities (DOE, 2013; Hauenstein, 2005).

*Impacts of increased temperatures*. As shown in Table 4.1, both the mean annual temperatures and the number of extreme heat days are expected to increase across all regions in the U.S. These increased temperatures will increase cooling needs in every region, while decreasing projected heating needs (Dell et al. 2014). This will increase the summer peak demands of the electricity system, as nearly all cooling energy is provided by electricity. A higher summer electricity peak will require increased usage of expensive and underutilized generation equipment and stress and reduce the capacity of transmission and distribution infrastructure (Sathaye et al. 2013). A regional reduction in heating needs can affect the amount of infrastructure required for fuel distribution and storage, as heating needs are supplied through electricity as well as natural gas, heating oil and other fuels. On the other hand, winter peak electricity needs would be reduced, further altering the need for natural gas and other fuels for electricity in the winter heating season.

Increased temperature could also affect energy generation infrastructure. Higher water temperatures could cause curtailments at thermoelectric plants using rivers for cooling in order to remain within thermal discharge limits. Hotter air and water temperatures will also reduce the efficiency of thermoelectric generation, requiring more fuel to produce similar amounts of electricity. Higher temperatures could also affect the available capacity of hydropower, solar PV, wind power and biofuel production, as well as threaten the stability of the Arctic oil and gas infrastructure located on permafrost (DOE, 2013). Given the very high likelihood of increased temperatures in the future (Dell et al. 2014), engineering decision making in the energy sector should recognize and plan for the potential impacts to long-term supply, distribution and demand.

*Impacts of decreased water availability.* Energy in the U.S. is enabled through water use. The production, transportation, refining and storage of fuels (e.g. oil and gas, coal, biomass), as well as power generation in coal, natural gas, nuclear, hydroelectric, biomass and solar thermal plants, require long-term access to water (DOE, 2013). Long-term precipitation changes, drought and reduced snowpack, coupled with increasing demands for water, are projected to alter water availability. The impacts will vary by region; longer dry spells are projected in the Northwest and seasonal water constraints are projected in the Southwest and Southeast (Dell et al. 2014). Reduced water flows and higher water temperatures limit the availability of river water use for thermoelectric power plant cooling, while reduced snowpack affects hydroelectric capacity.

Decreased water availability and prolonged droughts could affect oil and gas exploration, especially unconventional production relying on horizontal drilling and hydraulic fracturing. The costs and availability of conventional oil refining could also be affected, as the process requires between 0.5 and 2.5 gallons of water or more per gallon of gasoline equivalent (DOE, 2013). Reduced river water levels decrease the barge capacity of the inland water transportation system, which transports coal, oil and petroleum products. A one-inch drop in river capacity can reduce a barge tow's capacity by 255 tons on the upper Mississippi, Illinois and Ohio rivers, and by up to 765 tons on the lower Mississippi (DOE, 2013).

*Impacts of sea-level rise, storm surge and subsidence.* Sea levels have risen globally by about 8 inches since 1880 and are projected to rise 1 to 4 feet by 2100 (Dell et al. 2014). Sea-level rise amplifies the impacts of storm surges, and combined with local subsidence and high tides, can threaten coastal energy infrastructure. These include oil and gas infrastructure in the central Gulf Coast region and power plants and electricity infrastructure throughout the coastal United States (DOE, 2013; Dell et al. 2014). For coastal energy facilities to withstand future storm surges, the performance of existing structural measures should be reevaluated under future sea-level rise, storm surge and subsidence impacts (Brown et al. 2014). Similarly, a scale-up of future coastal thermoelectric power generation, including nuclear power, could face increased costs for hardening against sea-level rise and storm surge (Kopytko and Perkins, 2011).

*Approaches for adaptation decision making with climate uncertainty.* Infrastructure enabling the U.S. energy supply is designed for a useful life of several decades or more, and is expensive and time-consuming to construct and retrofit. Much of the existing coal and nuclear power plants in the U.S. were constructed during a building boom from the 1960s to the 1980s; decisions are currently being made about recapitalizing, retrofitting or retiring these and other existing energy assets. At the same time, new firms are deploying new infrastructure for renewables, natural gas power generation and unconventional hydrocarbon development. Infrastructure stakeholders in the private and public sectors need to design, construct and operate existing and future energy infrastructure to be resilient against climate change impacts. Energy infrastructure should be responsive to future energy demands as well as dramatically reduce associated greenhouse gas emissions, decrease air, water and waste impacts, and maintain competitive life cycle costs. This enormous challenge, coupled with the range of uncertainties regarding the timing, magnitude and location of climate change impacts, requires new approaches for engineering decision making for adaptation. These approaches must enable decisions in the face of uncertainty and should maximize low-regret alternatives, co-benefits of actions, and robustness under the range of future climate change impacts. Many of the elements of adaptation strategies for infrastructure can be based on existing knowledge (Wilbanks and Fernandez, 2013).

A near-term action is to conduct vulnerability assessments for new energy infrastructure and existing infrastructure with a high likelihood of impact risk (e.g., coastal power plants). Vulnerability assessments should inform the development of robust risk management strategies that iteratively incorporate observation, evaluation and learning (Wilbanks et al. 2013). The civil engineering community should also support data collection, monitoring and analysis of energy infrastructure to update these vulnerability assessments with empirical observations.

The next set of actions include those with low-regret—that is, those decisions that are likely to perform well in the face of climate uncertainty. Low-regret approaches include system designs and infrastructure to manage, store and shift electricity load in the transmission and distribution system, while dramatically reducing the greenhouse gas intensity of power generation. As specific energy infrastructure approaches the end of its service life, finding opportunities to reduce energy system sensitivities to water and temperature impacts could steadily recapitalize the system for resilience (Wilbanks et al. 2013). Other low-regret approaches could couple climate-resilient designs with other national priorities, such public health, economic growth, energy and national security (Bierbaum et al. 2014; DOE, 2013). Improving community resiliency and preparedness for disasters that disrupt energy services may create co-benefits across the planning for both climate and non-climate related disasters (DOE, 2013). Design standards for regional generation capacity reserve margins, power line capacity and distribution infrastructure could be established for performance in a set of expected future temperature, weather and demand conditions, which could be adjusted incrementally and holistically as new climate information becomes available (Dell et al. 2014). The World Bank (2011) described a set of structural, technological and behavioral adaptive measures for energy system infrastructure potentially affected by climate change, and the National Climate Assessment provided possible resilience measures for energy infrastructure. These actions are summarized in Table 4.3.

Finally, engineering stakeholders could transition to an integrated climate risk management framework to evaluate major infrastructure investments. This framework should include methods to introduce flexibility into infrastructure designs to manage uncertain future climate impacts and also uncertain future socioeconomic and policy trends (Wilbanks et al. 2013). In addition, these processes need to incorporate the values and goals of the stakeholders, the evolving scientific literature, the available information and the perception of risk (Moss et al. 2014; Chang et al. 2014). One applicable method is to use Robust Decision Making (RDM) (Lempert et al. 2006; Groves and Lempert, 2007), which is an iterative, quantitative approach designed for conditions of deep uncertainty, such as the timing and magnitude of climate change impacts. RDM has seen increasing application and success in areas focused on natural resources and water resources