A WORLD BANK STUDY

Climate Impacts on Energy Systems

KEY ISSUES FOR ENERGY SECTOR ADAPTATION

THE WORLD BANK

Jane Ebinger, Walter Vergara

W O R L D   B A N K   S T U D Y

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Energy Sector Management Assistance Program

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Preface

This report was produced by the Energy Sector Management Assistance Program (ESMAP) and the World Bank Group's Global Expert Team for Adaptation. It was conceived following a brainstorming discussion on the subject "Sustainable Energy Supply, Energy Access and Climate Change" hosted by ESMAP on October 26–27, 2009, and attended by 17 external specialists renowned for their work on development, energy, and climate change. This meeting challenged ESMAP to go beyond its work on climate mitigation in energy systems, and build upon and expand its pilot program on energy sector vulnerability to climate change to better understand and help inform operational teams on potential climate impacts and options for their management.

This report is intended as an up-to-date compendium of what is known about weather variability and projected climate trends and their impacts on energy service provision and demand. It discusses emerging practices and tools for managing these impacts and integrating climate considerations into planning processes and operational practices in an environment of uncertainty. It draws on published, peer-reviewed literature.

This report has been compiled to raise awareness of potential climate impacts and stress points on the energy sector. The target audiences are policy makers and energy planners and practitioners in developing countries.

Acknowledgments

This report was prepared by a core team led by Jane Ebinger at the Energy Sector Management Assistance Program (ESMAP) and Walter Vergara, heading the World Bank Group's Global Expert Team for Adaptation, who both edited this report with Irene Leino. The team is grateful for contributions from a range of authors engaged in research and analysis of climate change, development, and energy issues (below in alphabetical order). It was conducted under the general guidance of Amarquaye Armar, followed by Istvan Dobozi and Rohit Khanna in the role of Program Manager for ESMAP and benefited from peer review by Jonathan Coony, Alejandro Deeb, Daniel Kammen, and Marcelino Madrigal. The team was assisted by Irene Leino, Oeyvind Lier, and Vanessa Lopes.

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ESMAP

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GET-CCA

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Executive Summary

Energy services are a necessary input for development and growth. At the same time, fossil energy conversion, and end use, is recognized as a major contributor to global warming. Today 70 percent of greenhouse gas emissions (GHG) emissions come from fossil fuel combustion for electricity generation, in industry, buildings, and transport—and these emissions are projected to rise. By 2050, the global population will grow to 9 billion, with growth mostly concentrated in developing countries with improved living standards. If we continue as we are today, delivering energy services and sustaining economic growth will result in a tripling of annual GHG emissions (World Bank, 2009a).

Efforts are under way, in developed and developing countries, to arrest and reverse the growth in GHG emissions and lower the carbon footprint of development. The energy sector is a primary target of these efforts. Consequently, capacity is being built to integrate lower carbon development objectives into long-term (20 to 30-year) energy planning processes. Experience and knowledge of new technologies and measures to lessen carbon footprints are being exchanged. There is significant focus on the major scale-up of renewable energy sources, efficiency measures (supply and demand side), loss reduction, and cleaner fossil fuel combustion technologies.

But the climate is also changing as a result of anthropogenic GHG emissions that are now estimated to surpass the worst-case emission trajectory drawn under the Intergovernmental Panel on Climate Change (IPCC) in its third assessment report (IPCC, 2001a). This highlights the urgency of the above actions to control emissions. It also highlights the need to adapt to unavoidable climate consequences from the damage already induced in the biosphere. By 2050, we will see higher temperatures and sea levels, changes in sea surface conditions and coastal water quality, increased weather variability, and more frequent and extreme weather events, even if global GHG emissions are stabilized at 2°C above pre-industrial levels. Already the entire energy supply chain is significantly vulnerable to climate variability and extreme events that can affect energy resources and supplies as well as seasonal demand; the projected changes will increase this vulnerability and thus the need to adapt to changing conditions. In 2005 alone, climate extremes accounted for a 13 percent variation in energy productivity in developing countries (World Bank, 2010a).

To date, decision makers have focused on maximizing energy supplies to satisfy industrial and societal demand for energy while managing the risks perceived to be of immediate concern, including climate mitigation. The energy sector is under-represented in both peer-reviewed literature on adaptation and in related investment and action.

This report presents an overview of how the energy sector might be impacted by climate change and what options exist for its management. It focuses on energy sector adaptation, rather than mitigation, which has been a key focus of the energy sector and is not discussed in this report. This report draws on available scientific and peer-reviewed literature in the public domain and takes the perspective of the developing world to the extent possible.

It starts with a discussion about observed and projected climate change (out to 2100), exploring trends, extremes, and "hotspots"—geographic regions that will see significant changes or variability for relevant parameters (for example, temperature, runoff, and sea level rise). It then discusses what is known about the impacts of these changes on energy resources, infrastructure, and transportation systems as well as demand. It discusses what technologies or services are more vulnerable and identifies gaps in information or knowledge.

This is complemented by a discussion of emerging practices for energy sector adaptation, climate risk management, and decision making under uncertainty. This report considers the available and needed tools and services to support decision making and adaptation as well as the role of institutions and regulators in enabling action.

The report concludes with a number of proposed near-term actions to foster dialogue, to further inform sector practitioners, to disaggregate climate impacts to regional and local settings, and to improve the knowledge base. Underpinning all actions is recognition of the need for a broad and participatory approach that extends beyond traditional planning horizons and boundaries.

The key messages from this report are:

- **Energy services and resources will be increasingly affected by climate change—changing trends, increasing variability, greater extremes, and large inter-annual variations in climate parameters in some regions.** Though potential climate impacts have been recognized strongly within the energy sector, the focus has mainly been on the responsibility for greenhouse gas mitigation rather than on the management of energy services. Climate impacts cross the entire energy supply chain. Impacts on energy supply and demand are the most intuitive but there are also direct effects on energy resource endowment, infrastructure, and transportation, and indirect effects through other economic sectors (for example, water, agriculture).
- **All evidence suggests that adaptation is not an optional add-on but an essential reckoning on par with other business risks.** Both *existing energy infrastructure* and *new infrastructure and future planning* need to consider emerging climate conditions and impacts on design, construction, operation, and maintenance. Although energy systems already take account of some climate risks in their operation and planning,[1] adaptation measures can further reduce their vulnerability to environmental change by building capacity and improving information for decision making and climate risk management. Many actions increase a system's resilience to variations in climate, regardless of global climate change, and can be implemented at relatively low cost, since adaptation may have associated external benefits.[2]
- **Integrated risk-based planning processes will be critical to address these impacts and harmonize actions within and across sectors.** This will help to avoid locking in unsustainable practices today through investments in long-lived infrastructure and associated consumption patterns. It can support management of tradeoffs and challenges; for example, long-term planning for climate mitigation needs to recognize and integrate energy sector impacts and adaptation strategies; and more remains to be done to optimize energy and water resource management. Planning processes should be underpinned by broad stakeholder engagement.

- **Awareness, knowledge, and capacity impede mainstreaming of climate adaptation into the energy sector.** The formal knowledge base is still nascent—information needs are complex and to a certain extent regionally and sector specific. The capacity to use information is challenged by a lack of access to tailored, reliable, and timely observations and predictions; limited experience in dealing with associated uncertainties; as well as the availability of research, guidance, and practice on energy sector adaptation. These issues are exacerbated in developing countries, where there is often a dearth of historical hydro-meteorological data and limited capacity to provide climate services.

Energy Services Will Be Increasingly Affected By Climate Change

Observed Climate Change. The best available (global) baseline over which to assess future climate changes is the *observed* climate in the recent past. Various hydro-meteorological and climate factors have the potential to affect the energy sector (Table ES.1). Some impacts may be systemic. For example, changes in mountain hydrology will affect the firm energy of an entire hydropower system over a large geographical area. Others may be localized, such as impacts of extreme weather events on energy infrastructure in low-lying coastal areas.

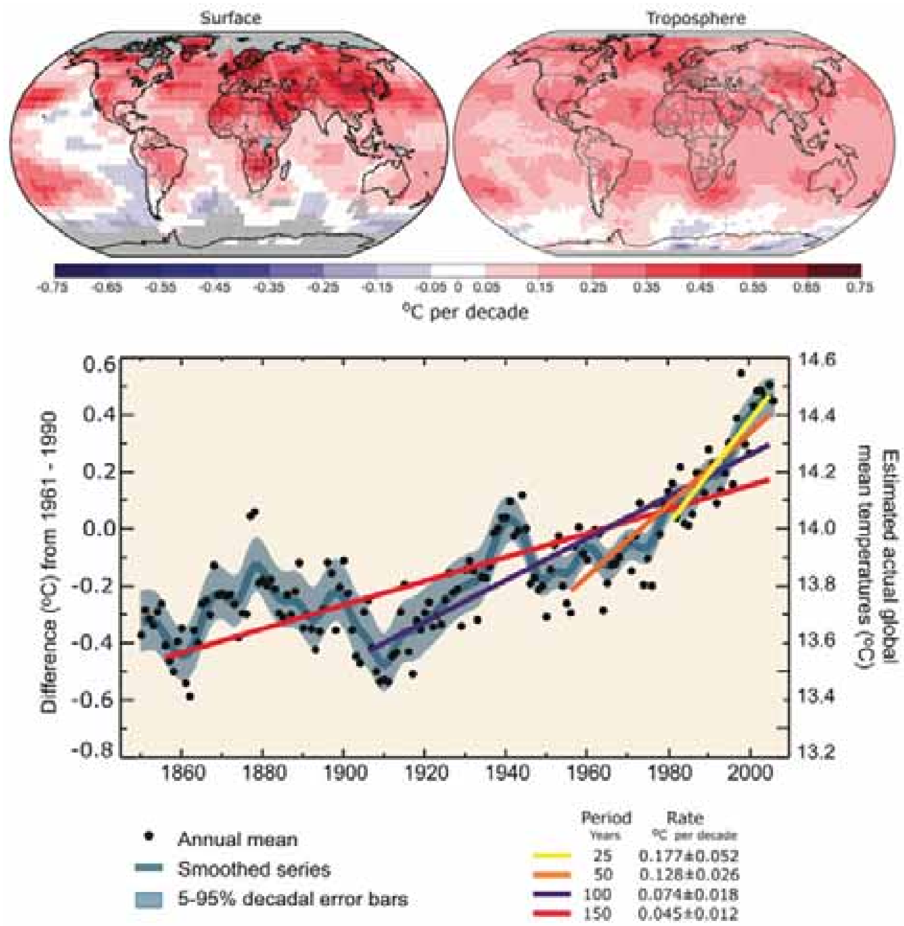
Table ES.1. Hydro-meteorological and Climate Parameters for Select Energy Uses

Hydro-meteorological and/or climate parameter	Select energy uses
Air temperature	Turbine production efficiency, air source generation potential and output, demand (cooling/heating), demand simulation/modeling, solar PV panel efficiency
Rainfall	Hydro-generation potential and efficiency, biomass production, demand, demand simulation/modeling
Wind speed and/or direction	Wind generation potential and efficiency, demand, demand simulation/modeling
Cloudiness	Solar generation potential, demand, demand simulation/modeling
Snowfall and ice accretion	Power line maintenance, demand, demand simulation/modeling
Humidity	Demand, demand simulation/modeling
Short-wave radiation	Solar generation potential and output, output modeling, demand, demand simulation/modeling
River flow	Hydro-generation and potential, hydro-generation modeling (including dam control), power station cooling water demands
Coastal wave height and frequency, and statistics	Wave generation potential and output, generation modeling, off-shore infrastructure protection and design
Sub-surface soil temperatures	Ground source generation potential and output
Flood statistics	Raw material production and delivery, infrastructure protection and design, cooling water demands
Drought statistics	Hydro-generation output, demand
Storm statistics (includes strong winds, heavy rain, hail, lightning)	Infrastructure protection and design, demand surges
Sea level	Offshore operations, coastal energy infrastructure

Source: Generated by authors.

"Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases" (IPCC, 2007c). Global average surface temperature has increased with the rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) and is nearly twice that of the last 100 years (Figure ES.1). Re-analyses show a positive trend in global solar radiation at the surface over land, but negative globally.

Figure ES.1. (Top) Patterns of Linear Global Temperature Trends over the Period 1979 to 2005



Source: IPCC, 2007a.

Note: Estimated at the surface (left), and for the troposphere from satellite records (right). Gray indicates areas with incomplete data. (Bottom) Annual global mean temperatures (black dots) with linear fits to the data. The left-hand axis shows temperature anomalies relative to the 1961 to 1990 average and the right-hand axis shows estimated actual temperatures, both in °C. Linear trends are shown for the last 25 (yellow), 50 (orange), 100 (magenta), and 150 years (red). The smooth blue curve shows decadal variations, with the decadal 90 percent error range shown as a pale blue band about that line. The total temperature increase from the period 1850 to 1899 to the period 2001 to 2005 is 0.76°C ± 0.19°C.

Natural systems related to snow, ice, and frozen ground (including permafrost) and hydrological systems are affected. The melting of ice sheets, glaciers, and ice caps has accelerated and sea levels have risen an average of 18 cm since the late 19th century. It is likely that the frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas.

Extreme weather events have also changed in frequency and intensity since 1950. It is very likely that cold days, cold nights, and frosts have become less frequent over most land areas, while hot days and hot nights have become more frequent. It is likely that heat waves have become more frequent over most land areas. A modest change in the wind climate of some regions has been observed, with an increase in intense tropical cyclone activity in the North Atlantic since about 1970 (although there is less confidence in this statement). There is emerging evidence of variability in climate parameters.

Besides trends, intra- and inter-annual climate variations are important for energy planning and operations. Europe and Central Asia is the only region with observed large inter-annual temperature variations; up to about 5°C in winter months (Table ES.2). Since a large portion of this region is covered in permafrost, the energy industry is vulnerable to these large temperature variations (for example, structural integrity of pipelines). Large deviations in near-surface wind speed have been observed over the oceans and, typically, during the colder season. Offshore operations in the Gulf of Mexico (particularly in the winter season) and areas in northwest Africa are exposed.

Table ES.2. Summary Table of "Hotspots"

	Africa	East Asia & Pacific	Europe & Central Asia	Latin America & Caribbean	Middle East & North Africa	South Asia
2-meter T	Sizeable projected changes in variability	Large errors in observed seasonal mean	Large observed variability; sizeable projected changes in variability	Large errors in observed seasonal mean; sizeable projected changes in variability		Large errors in observed seasonal mean
10-meter wind				Large observed variability over ocean	Large observed variability over NW Africa	
Solar radiation	Large errors in observed annual mean; sizeable projected changes in high-end extremes			Large errors in observed annual mean	Sizeable projected changes in high-end extremes	Large errors in observed annual mean; sizeable projected changes in high-end extremes
Sea level	Large observed changes					Large observed changes
Permafrost			Risk of degradation and reduction			
Sea ice	Reported acceleration of melting of Greenland and Antarctic ice sheets					

Source: Generated by authors.
Note: Hotspots listed were identified in Chapter 2, sections "Climatic Impacts on Energy Services" and "Recent Observed Climate Change," and hence are not comprehensive across all variables/statistics combinations. "Observed" refers to either direct observations or to outputs from re-analyses.

Expected Climate Change. Anthropogenic climate change for the next several decades is very hard to estimate due to what can be expressed as noise in the climate change signal caused by inter-annual climate variability. There are, however, a number of robust trends already identified, on the basis of which future estimates can be drawn. These trends include the increases in temperatures in the lower atmosphere and sea surface, increases in sea level rise, reduction of wetness in topsoil layers, and others. However, there continues to be uncertainty about the future pace of change, and not all climate parameters have the same degree of variability. Average temperatures are more robust than precipitation values, for example.

It is evident that all land regions are very likely to warm during the 21st century. Geographical patterns of projected warming of surface temperatures are scenario-independent, with the greatest temperature increases over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean, consistent with the observed changes during the latter part of 20th century (Appendix D for regional picture) and over mountain regions. The western part of Europe and Central Asia, West Africa, and several parts of Latin America and the Caribbean are projected to experience increasing levels of temperature variability (Table ES.2).

Summertime melting of Arctic sea ice has accelerated far beyond the expectations of climate models: the area of summertime sea ice during 2007–2009 was about 40 percent less than the average prediction from IPCC Fourth Assessment Report (AR4) climate models (about 8 million km^2). According to Holland et al. (2006), the Arctic summer could become nearly ice-free by 2040. Although this estimate requires further testing and verification, strong Arctic warming is enough to substantially reduce the total area of near-surface permafrost by 2100 in all climate models that incorporate this phenomenon. Permafrost degradation of this magnitude is likely to invoke a number of [unspecified] hydrological, biogeochemical, and ecological feedbacks in the Arctic system (Lawrence et al., 2008), including the potential release of a considerable amount of methane (CH_4). Global sea level is likely to rise at least twice as much as projected by Working Group 1 of the IPCC AR4 by the end of the century (the range was 18–59 cm); for unmitigated emissions it may well exceed 1 meter. More important, for hydropower regions, the volume of mountain glaciers has significantly decreased, in particular in tropical areas, and in some regions a process of mountain desertification has been documented.

Rising temperatures will also reduce the thermal difference between polar regions and the tropics and mean mid-latitude wind speeds will decrease; wind trend studies in selected areas indicate that this may indeed be happening. Though changes in high-end extreme values need to be accompanied by other statistical measures (for example, changes in mean values), they can provide an indication of how peak solar energy production could vary. An overall reduction is projected over sub-Saharan Africa (especially in the eastern part) and an increase by more than 5 watts per square meter ($W\ m^{-2}$) over the Middle East.

Climate projections using multi-model ensembles show increases of globally averaged mean water vapor, evaporation, and precipitation over the 21st century. The models indicate that precipitation generally increases at high latitudes in both winter and summer seasons, and in areas of regional tropical precipitation maxima (such as the monsoon regimes, and the tropical Pacific in particular), with general decreases in the subtropics. However, it is uncertain how rainfall will evolve in the 21st century for a large number of regions and seasons, in particular in West Africa and South America in winter, summer, and for the annual mean; in Central Asia in winter and for the annual mean; as well as in South Asia in winter. Taking the case of Africa, this means that there will be regions with a projected increase in precipitation, others with a decrease, and quite large areas where the models disagree so that at present it is not possible to make a reliable projection. This regional diversity has to be kept in mind.

Evaporation, soil moisture, and runoff and river discharge are also key factors. Under the Special Report on Emission Scenarios (SRES) A1B scenario, the ensemble mean shows that runoff will be notably reduced in the Mediterranean region and increased in South East Asia and in high latitudes, where there is consistency among models in the signs of change. Precipitation changes due to warming could lead to changes in the seasonality of river flows. In regions where winter precipitation currently falls as snow, spring flows may decrease because of the reduced or earlier snowmelt, and winter flows may increase. In many cases peak flows by the middle of the 21st century would occur at least a month earlier.

There is a wider consensus among models that the water cycle will intensify, with more intense periods of rainfall and the lengthening of dry periods. Most climate models project precipitation intensity increases almost everywhere, particularly in tropical and high-latitude areas that experience increases in mean precipitation. Models also project a tendency for drying in mid-continental areas during summer, indicating a greater risk of droughts in these regions. Storm intensities may increase in a warmer atmosphere, but Pielke et al. (2005) claim that linkages between global warming and hurricane impacts are premature.

Impacts on Energy Services

Climate change will increasingly affect the energy sector. Although impacts on energy supply and demand are the most intuitive, climate change can also have direct effects on energy endowment, infrastructure, and transportation, and indirect effects through other economic sectors. This exposure is driven in part by the current state of the sector (for example, inefficiencies in energy and water use mean energy services are vulnerable to water variability and have less capacity to deal with change).

Given the intergenerational character of energy planning decisions, the long life span of energy infrastructure—15–40 years for power plants and 40–75 years for transmission lines—and the expected rise in energy demand, it is important to understand the potential vulnerabilities of energy services due to climate consequences. But it is not a straightforward process to assess the actual impact of these changes. The formal knowledge base is still at an early stage of development (Willbanks et al., 2007), particularly for assets that are indirectly weather dependent (for example, thermal power, transmission). Renewable energy plays a key role in future low-carbon-emission plans aimed at limiting global warming. However, its dependence on climate conditions makes it also susceptible to climate change. Although the first part of this "paradox" has been thoroughly studied (IPCC, 2007c), the international scientific community has only recently started to investigate the impacts that global climate change may have on energy, in general, and renewable energy, specifically.[3]

There are, however, certain guidelines that might be offered, assuming that the climate does not pass any tipping points for rapid change:

- Increasing temperatures are almost certain to reduce heating demands but increase cooling demands overall, but inter-annual variability will remain and cold periods (such as experienced widely over part of the Northern Hemisphere during the 2009–2010 winter) will not disappear. Seasonal demand profiles will alter responding to user needs for energy for heating and cooling in buildings, for industrial processes, and for agriculture (for example, irrigation). Temperature tolerances of energy sector infrastructure may be tested more regularly, as may those of cultivated biofuels. Infrastructure on permafrost will be affected.

- Flooding and droughts will continue; it may be advisable to include contingencies for increased intensities and frequencies in risk management, even if no guarantees can be given that either or both will occur at any location. Impacts on infrastructure (including silting of reservoirs), on demand, on the production of biofuels, and on hydro-generation should be considered.
- Sea level rise is unavoidable, and could be accompanied by increased risk of coastal storm damage even should storms not intensify. Potential issues include risks to offshore infrastructure, including production platforms and wave and tidal generators.
- Increases in cyclonic storm intensities, at both tropical and extra-tropical latitudes, have a greater than 66 percent chance of occurring as a detectable change, according to the IPCC AR4 report. In addition to flooding and offshore risks, such storms may bring increased wind speeds at times, both at sea and over land. Infrastructural issues may result; tolerances of wind generators may be tested.
- Low-lying coastal and offshore infrastructure may be impacted by extreme events (for example, hurricanes), flooding sea level rise, and storm surges that can disrupt production and affect structural integrity
- Climate change may impact the generation cycle efficiency and cooling water operations of fossil-fuel-fired, nuclear, and biomass-fired power plants
- Changes in weather variability and frequency of extreme events would affect required stocks of fuels or installed nominal generation capacities, thus increasing operational and maintenance costs.
- The generation potential of renewables may change but is impossible to assess without additional locally specific study:
  - Hydro-generation may benefit or suffer, or both at different times, from changes in rainfall.
  - Solar generation may not be affected in a substantial manner, although some regions may see future decreased generation.
  - Ground source generation is unlikely to be influenced.
  - Wind generation may be impacted either positively or negatively by local adjustments to the wind regime.
  - Biomass/biofuel generation could be affected by changes in cultivation regimes.
  - Wave generation may gain should offshore storms intensify.
  - Tidal generation might be influenced by higher sea levels, although intuitively any effects may be minor.
- Energy transportation infrastructure (for power, oil, and gas) are variously exposed to wind gusts, storms, icing, storm-related landslides and rockfalls, land movements, siltation and erosion processes, as well as changes in water basins.
- Climate will impose a new set of conditions on the design, operation, and maintenance of existing and planned infrastructure. Balancing water availability with demand from multiple sectors will be increasingly difficult, as rising demand and new technologies may require more water in areas facing reduced availability.

Table ES.3 summarizes potential impacts on the energy sector.

Table ES.3. Energy Sector Vulnerability to Climate Change

	Relevant climate impacts			
Item	**General**	**Specific**	**Additional**	**Impacts on the energy sector**
Climate change impacts on resource endowment				
Hydropower	Runoff	Quantity (+/-) Seasonal flows high & low flows Extreme events	Erosion Siltation	Reduced firm energy Increased variability Increased uncertainty
Wind power	Wind field characteristics, changes in wind resource	Changes in density, wind speed Increased wind variability	Changes in vegetation (might change roughness and available wind)	Increased uncertainty
Biofuels	Crop response to climate change	Crop yield Agro-ecological zones shift	Pests Water demand Drought, frost, fires, storms	Increased uncertainty Increased frequency of extreme events
Solar power	Atmospheric transmissivity	Water content Cloudiness Cloud characteristics	Pollution/dust and humidity absorb part of the solar spectrum	Positive or negative impacts
Wave and tidal energy	Ocean climate	Wind field characteristics No effect on tides	Strong nonlinearity between wind speed and wave power	Increased uncertainty Increased frequency of extreme events
Climate change impacts on energy supply				
Hydropower	Water availability and seasonality	Water resource variability Increased uncertainty of expected energy output	Impact on the grid Wasting excessive generation Extreme events	Increased uncertainty Revision of system reliability Revision of transmission needs
Wind power	Alteration in wind speed frequency distribution	Increased uncertainty of Energy output.	Short life span reduces risk associated with Climate change Extreme events	Increased uncertainty on energy output
Biofuels	Reduced transformation efficiency	High temperatures reduce thermal generation efficiency	Extreme events	Reduced energy generated Increased uncertainty
Solar power	Reduced solar cell efficiency	Solar cell efficiency reduced by higher temperatures	Extreme events	Reduced energy generated Increased uncertainty
Thermal power plants	Generation cycle efficiency Cooling water availability	Reduced efficiency Increased water needs, for example, during heat waves	Extreme events	Reduced energy generated Increased uncertainty
Oil and gas	Vulnerable to extreme events	Cyclones, floods, erosion and siltation (coastal areas, on land)	Extreme events	Reduced energy generated Increased uncertainty

(continued)

Table ES.3 (continued)

	Relevant climate impacts			
Item	**General**	**Specific**	**Additional**	**Impacts on the energy sector**
Impacts on transmission, distribution, and transfers				
Transmission , distribution, and transfers	Increased frequency of extreme events Sea level rise	Wind and ice Landslides and flooding Coastal erosion, sea level rise	Erosion and siltation Weather conditions that prevent transport	Increased vulnerability of existing assets
Impacts on design and operations				
Siting infrastructure	Sea level rise Increased extreme events	Flooding from sea level rising, coastal erosion Increased frequency of extreme events	Water availability Permafrost melting Geomorphodynamic equilibrium	Increased vulnerability of existing assets Increased demand for new good siting locations
Downtime and system bottlenecks	Extreme weather events	Impacts on isolated infrastructure Compound impacts on multiple assets in the energy system	Energy system not fully operational when community requires it the most	Increased vulnerability Reduced reliability Increased social pressure for better performance
Energy trade	Increased vulnerability to extreme events	Cold spells and heat waves	Increased stress on transmission, distribution, and transfer infrastructure	Increased uncertainty Increased peak demand on energy system
Impacts on energy demand				
Energy use	Increased demand for indoor cooling	Reduced growth in demand for heating Increased energy use for indoor cooling	Associated efficiency reduction with increased temperature	Increased demand and peak demand, taxing transmission and distribution systems
Other impacts				
Cross-sector impacts	Competition for water resources Competition for adequate siting locations	Conflicts in water allocation during stressed weather conditions Competition for good siting locations	Potential competition between energy and nonenergy crops for land and water resources	Increased vulnerability and uncertainty Increased costs

Source: Generated by authors.

Adaptation Is Not an Optional Add-on

In the global climate change context, adaptation requires a combination of elements that include the availability of economic and natural resources, access to technology and information, and infrastructure and institutions (Smit et al., 2001). The main objective of adaptation as defined by the IPCC is "*to moderate harm or exploit beneficial opportunities*" (IPCC, 2007d). In the case of the energy system, the primary objective of adaptation could be interpreted as *guaranteeing the supply of sustainable energy, and balancing production and consumption throughout time and space*.

Adaptation measures can be taken as a response to climate change alone, as part of a broader set of initiatives (Adger et al., 2007), or as an addition to baseline investments for the purpose of increasing resiliency. There are many similarities between adaptation (in the climate change context) and measures taken by individuals, firms, or governments to deal with the natural (current) climate variability and the variability created by global climate change (Callaway, 2004). Therefore, dissociating climate change adaptation from energy policy can be complicated, especially when there are many no-regret actions.

Energy systems already take account of some climate risks in their operation and planning.[4] Adaptation measures can further reduce their vulnerability to environmental change, by building capacity and improving information for decision making, and integrating climate risks into management and operational decisions. Adaptation measures that fall into this general category span improvements in weather/climate information; the coupling of climate and energy analysis by adapting climate data to energy system needs; addressing current inefficiencies in the use of available resources; and energy sector diversification. Many actions increase a system's resilience to variations in climate, regardless of global climate change, and can be implemented at relatively low cost, since adaptation may have associated external benefits.[5] ECA (2009) finds, based on case studies, that between 40 and 68 percent of the loss expected to 2030 under severe climate change scenarios could be averted through adaptation measures whose economic benefits outweigh their costs. Examples of no-regret energy options in the African context include early warning systems, energy investment, diversification of energy generation, technology transfer, and energy efficiency (HELIO International, 2007).

Adapting to climate change has to be understood as an ongoing process. A critical step in ensuring energy system resilience is to build adaptive capacity, defined as "*the ability or potential of a system to respond successfully to climate variability and change*" (Adger et al., 2007). It reflects fundamental conditions such as access to information (research, data collecting and monitoring, and raising awareness), and institutional development (supportive governance, partnerships, and institutions). Climate adaptation measures in the energy sector are critically dependent on reliable and timely weather and hydro-meteorological observations combined with forecast models (for example Numerical Weather Prediction models) and assessment tools specific for the energy sector (Troccoli, 2009).

It is equally important to link climate knowledge with action and persuade businesses, communities, and individuals to adjust their behavior in ways that promote adaptation and limit emissions (UNEP, 2006). This requires information to be relevant, technically sound, and user-oriented. Successful adaptation involves collaboration across a multitude of interested partners and decision makers: international, national, and local governments, the private sector, nongovernmental organizations and community groups, and others that all have important roles to play. For example, it is critical to facilitate dialogue between weather-water-climate scientists and energy decision makers to address cross-cutting issues for energy production, access, and efficiency.

There are several ways to adapt, as described next.

Preventing Effects or Reducing Risks. Certain effects of climate change will be almost unavoidable (IPPC AR4), and one focus of adaptive actions should therefore be to alleviate or minimize these negative effects. Table ES.4 offers examples of technological and behavioral adaptation measures in the energy sector intended to minimize negative impacts due to long-term changes in climatic conditions and extreme events.

A *technological* adaptation strategy invests in *protective infrastructure* to provide physical protection from the damages and loss of function that may be caused by climate-related extreme events. Targeted refurbishing can help to increase the robustness of weaker elements of energy assets with typical life spans of several decades. Furthermore, improvements in design standards can increase the resilience of new infrastructure. For example, where permafrost is melting,[6] deeper pilings can be used, and buildings can be raised slightly above the ground and thickly insulated.

There are also *behavioral* adaptation strategies. A first option for adapting energy infrastructure to climate change is to *reconsider the location* of investments. For example, the concentration of energy infrastructure along the Gulf Coast could be particularly costly if climate change leads to more frequent and intense storm events, and it could be in the interest of energy producers to shift their productive capacity to safer areas.[7] *Anticipating* the arrival of a climate hazard by using improved meteorological forecasting tools or better communication with meteorological services is another example of a behavioral strategy. These measures will require complementary actions such as the support of emergency harvesting of biomass in the case of an alert for rainfall or temperature anomalies. *Changes in the operation and maintenance* of existing infrastructure such as actions to adapt hydropower operations to changes in river flow patterns are another example.

The energy sector can share responsibilities for losses and risks by hedging weather events through the use of financial instruments. Examples include weather derivatives (typical of high-probability events, for example, a warmer-than-normal winter) and insurance (for low-probability but catastrophic events, for example, hurricanes) to protect against adverse financial effects due to variations in weather/climate. The level of diversification of an energy system also has a profound influence on the sector's resilience to climate impacts. Having alternative means to produce energy can reduce the vulnerability of the sector as a whole to a specific set of climate impacts (for example, hotter or dryer climate). Karekezi et al. (2005) identifies the lack of diversification of energy sources in East Africa as of particular concern. The study notes that East Africa relies on hydropower for almost 80 percent of its electricity.

Exploiting Opportunities. Energy/water saving and demand-side management measures provide a cost-effective, win-win solution for mitigation and adaptation concerns in a context of rising demand and supply constraints. Adapting to variations in building energy demand involves: reducing energy demand (especially) for cooling; and for the specific case of electricity, compensating for impacts that coincide with peak demand (demand-side management). Energy storage technologies are a further option to shift electricity consumption away from peak hours. However, energy efficiency gains are not just restricted to compensating for increased energy demand. Malta's smart grid solution (Goldstein, 2010) is an interesting example of electricity/water saving achieved

Table ES.4. Examples of Adaptation Measures to Reduce Losses/Risks in Energy Systems

ENERGY SYSTEM		TECHNOLOGICAL		BEHAVIORAL		
		"Hard" (structural)	"Soft" (technology and design)	Re(location)	Anticipation	Operation and maintenance
SUPPLY	**MINED RESOURCES (inc. oil and gas, thermal power, nuclear power)**	Improve robustness of installations to withstand storms (offshore), and flooding/drought (inland)	Replace water cooling systems with air cooling, dry cooling, or recirculating systems Improve design of gas turbines (inlet guide vanes, inlet air fogging, inlet air filters, compressor blade washing techniques, etc.) Expand strategic petroleum reserves Consider underground transfers and transport structures	(Re)locate in areas with lower risk of flooding/drought (Re)locate to safer areas, build dikes to contain flooding, reinforce walls and roofs	Emergency planning	Manage on-site drainage and runoff Changes in coal handling due to increased moisture content Adapt regulations so that a higher discharge temperature is allowed Consider water re-use ad integration technologies at refineries
SUPPLY	**HYDROPOWER**	Build de-silting gates Increase dam height Construct small dams in the upper basins Adapt capacity to flow regime (if increased)	Changes in water reserves and reservoir management Regional integration through transmission connections	(Re)locate based on changes in flow regime		Adapt plant operations to changes in river flow patterns Operational complementarities with other sources (for example natural gas)
SUPPLY	**WIND**		Improve design of turbines to withstand higher wind speeds	(Re)locate based on expected changes in wind-speeds (Re)locate based on anticipated sea level rise and changes in river flooding		
SUPPLY	**SOLAR**		Improve design of panels to withstand storms	(Re)locate based on expected changes in cloud cover	Repair plans to ensure functioning of distributed solar systems after extreme events	
SUPPLY	**BIOMASS**	Build dikes Improve drainage Expand/improve irrigation systems Improve robustness of energy plants to withstand storms and flooding	Introduce new crops with higher heat and water stress tolerance Substitute fuel sources	(Re)locate based in areas with lower risk of flooding/storms	Early warning systems (temperature and rainfall) Support for emergency harvesting of biomass	Adjust crop management and rotation schemes Adjust planting and harvesting dates Introduce soil moisture conservation practices
DEMAND		Invest in high-efficiency infrastructures and equipment Invest in decentralized power generation such as rooftop PV generators or household geothermal units		Efficient use of energy through good operating practice		
TRANSMISSION AND DISTRIBUTION		Improve robustness of pipelines and other transmission and distribution infrastructure Burying or cable re-rating of the power grid		Emergency planning	Regular inspection of vulnerable infrastructure such as wooden utility poles	

Source: Adapted from HELIO International 2009.

by building a smart grid to govern both water and electricity. The grid will quickly pinpoint theft, leakage, and defective meters and will promote the efficient use of the resources through pricing options that will reward solar energy and conservation. The transport sector provides another example. Here improvements in vehicle efficiency could compensate for the increased use of air conditioning.

As existing infrastructure ages there may be a new window of opportunity to build a more *decentralized energy structure*, based on locally available renewable energy sources situated in secure locations. This would reduce the probability of suffering large-scale outages when centralized power systems are compromised. This sort of regional, network-based system might also prove more flexible and adaptive, and therefore more able to cope with the increasing variability and unpredictability caused by environmental change.

And finally, cities are important and growing consumers of energy. Thus, urban policy and land-use planning will play an important role in improving the resilience of the energy system. There is a wide range of examples of urban initiatives to reduce energy consumption and improve resilience (ETAP, 2006), but there are also supply-side opportunities to be exploited. The electricity industry (Acclimatise, 2009) recognizes that it will face major challenges in providing new generation capacity and supply reliability within urban areas and that in the future industry members will need to develop a new supply and demand system where consumers can also be suppliers with a variety of home generators.

Integrated Risk-Based Planning Processes Will Be Critical

To increase climate resiliency, climate change adaptation also needs to be integrated into energy planning and decision-making processes at all relevant levels. Equally, energy sector responses to climate change need to be considered in the broader development context:

> *Responding to climate change involves an iterative risk management process that includes both mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity and attitudes to risk. Risk management techniques can explicitly accommodate sectoral, regional and temporal diversity, but their application requires information about not only impacts resulting from the most likely climate scenarios, but also impacts arising from lower-probability but higher-consequence events and the consequences of proposed policies and measures* (IPCC 2007b, p. 64).

While the fundamentals of risk management are already widely appreciated and practiced within the energy sector (for example, in planning and investment strategies for renewable energy), climate change does not appear to have been considered as a major risk for existing infrastructure or future plants, and many hydro-meteorological/climate-adaptation-related risks fall well below the "radar."

Climate risk assessment (CRA) and climate risk management (CRM)[8] can provide an integrated framework to guide decisions and actions (Table ES.5). The main advantage of an integrated assessment, as opposed to sector-specific analysis, is that it allows the indirect impacts of adopting a set of adaptation measures to be examined. Since there is competition for resources within the energy sector, as well as between the energy and other sectors, adapting to climate change impacts can have repercussions throughout the

Table ES.5. Climate Risk Management Processes

<table>
<tr><td rowspan="3">Climate Risk Assessment (CRA): an assessment of the vulnerabilities/risks posed to a project throughout its life cycle by weather and climate variability that might include:*</td><td>Impacts of adverse (or favorable) weather, such as storms and floods</td></tr>
<tr><td>Impacts of adverse (or favorable) climate variability, including droughts</td></tr>
<tr><td>Long-term impacts, beneficial and detrimental, associated with climate change</td></tr>
<tr><td colspan="2">Climate Risk Management (CRM): proactive management of a project to mitigate the negative (and promote the positive) impacts of weather and climate variability and of climate change, based on a CRA and using all available information, including predictions on all time scales</td></tr>
<tr><td colspan="2">Climate Proofing: actions taken to lessen, or perhaps eliminate, the potential negative impacts through the life cycle of a project of weather and climate variability and of climate change based on a CRA and on CRM principles</td></tr>
<tr><td colspan="2">Pollution Modeling: an assessment and predictions of ground and atmospheric pollution emitted during the life cycle of a project</td></tr>
<tr><td colspan="2">Emissions Modeling: numerical calculation of the amount of greenhouse gases released through the life cycle of a project</td></tr>
<tr><td colspan="2">Environmental Impacts Assessment (EIA): an assessment of the impacts on the environment in toto of an project during its entire life cycle, including on the ground, on the scenery, on the atmosphere, on flora and fauna, and on society</td></tr>
</table>

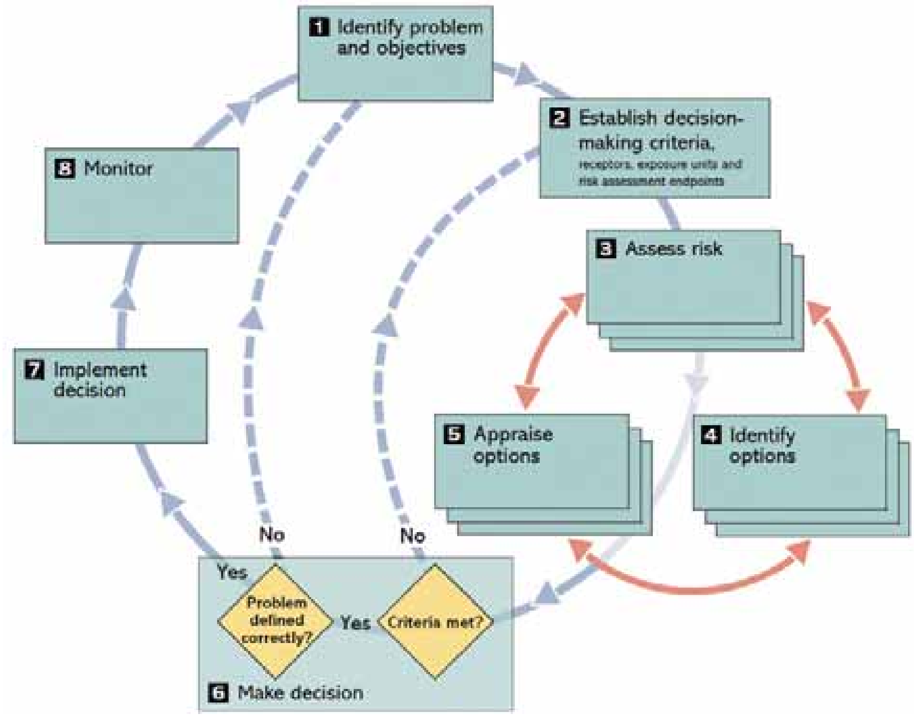
Source: Generated by authors.
Note: *The World Bank and other organizations, refer to CRA and the planning of climate proofing together as "climate risk screening" or equivalent (World Bank, 2010c).

economy. In fact, adaptation may involve not only different sectors, but also different agents. This happens because there are many indirect impacts of climate change in the energy sector, as well as indirect impacts on other economic sectors through impacts on energy.

Proper integration of climate risks in decision-making processes will minimize the risk of over-, under-, and maladaptation. There is a close link with decision-making criteria (Figure ES.2): *What is the "right" level of adaptation? How climate resilient do we want our actions to be?* Willows and Connell (2003) suggest that decision makers can identify climate conditions that represent *benchmark levels of climate risk*, against which they can plan to manage. The benchmarks may be based on past experience of climate and weather events (floods, droughts, hurricanes, and so forth) or on expected climate futures. They *represent a defined threshold between tolerable and intolerable levels of risk,* and provide a basis for developing practical risk assessments (Willows and Connell, 2003). As information becomes available in the risk management process, benchmarks may be revisited. For example, it may turn out to be prohibitively expensive or unfeasible to stay within the original benchmark level of risk.

Integrated planning is also highly important (Haas et al., 2008). Adaptation action may be required for an entire energy system or involve interactions between different segments of the energy sector or other sectors such as water or agriculture. For example, energy and water systems are closely linked. The production/consumption of one resource cannot be achieved without making use of the other. And, climate change affects the supply of both resources. Therefore, policy makers cannot provide a good adaptation plan without integrating both sectors as parts of a single strategy. From an energy perspective, competition for water can create stresses in a dryer climate due to the high water demand for power generation (mainly hydroelectricity, thermal power, and nuclear energy). The availability of water will have regional implications and directly affect the planning and siting of new capacity and the development of new technologies (Bull et al., 2007). Water resource management will therefore become an increasingly impor-

Figure ES.2. Framework for Climate Change Adaptation Decision Making under Uncertainty (UKCIP)



Source: Willows and Connell, 2003.

tant tool for solving conflicts and optimizing the use of natural resources for energy and other uses. There are similar examples on the agriculture side, where integrated policies and plans may be needed to offset competition between energy and nonenergy crops.

Integration is also required across stakeholders. Climate risk management requires an interdisciplinary effort and participatory approach where the tools and knowledge of scientists, energy analysts, and economists, policy makers and planners, and citizens are combined. Climate adaptation is also a local phenomena, requiring action tailored to the setting or context. The large investment required to adapt means that the public and private sectors at all levels will be part of the solution. Indeed, coping strategies are likely to be in use today and with the right processes to support the engagement of all relevant stakeholders can be tapped to increase national and regional resilience. Joint action will therefore be important both for planning and implementation of adaptation strategies.

Last, integration is required between climate adaptation and mitigation in an energy context. Energy diversification, demand-side management, and energy efficiency, for example, support adaptation as well as mitigation. But there can be tradeoffs. Changing climate parameters may increase energy demand and consumption (for example, for cooling and heating), and mitigation policies that hinge on larger shares of renewable energy sources are very likely to affect risk management practices, to influence technology research and development, and to affect energy choices (Wilbanks et al., 2008).

Moreover, if mitigation policies fail to integrate climate impacts on renewable energy sources, then this could impose severe risks of maladaptation.

There is a need for research and practical tools to address all aspects of risk management under climate uncertainties. The International Finance Corporation (IFC) summarizes the risk issue for private concerns in a manner that is also relevant for the public sector:

> *Climate change poses a series of risks to all private sector companies … yet a question still remains—how to measure that risk? This is a question the private sector has not addressed yet, lacking so far baseline information, methodology and strategy. This may pose significant challenges, in particular in developing countries where the impacts are expected to be the most significant. Methodologies for assessing some of these risks exist, but not with data and tools tailored to the needs of private sector investors and government decision makers (IFC, 2010a).*

There are additional needs to build capacity to model and project climate impacts at local and regional scales (for gradual changes and changes in variability), translate scientific data and knowledge into information relevant to decision making on adaptation, as well as to provide "order of magnitude" estimates of likely climate-related impacts on societies and economies.

Awareness, Knowledge, and Capacity Impede Mainstreaming of Climate Adaptation

To understand vulnerability, information is required on the nature and timing of the climate change, and the consequences for the energy sector. This requires access to data, modeling, and forecasting skills that are relevant to the energy industry, and this access needs to be provided in a timeframe compatible with investment, operations, and maintenance decisions, as well as for emergency planning. Decision makers, whether energy providers or energy users, require information not necessarily on hydro-meteorological/climate parameters *per se* but on how those parameters affect all stages of energy production, distribution, and demand. Naturally, climate is only one factor in determining, say, demand, but it is a key factor. Future demand will depend on factors such as development policies, on entrepreneurship, on population growth, on changing consumer distributions and transport links, on poverty reduction, on improved efficiencies in energy use, and so on, as well as on future climate. Many of those factors are or will be themselves influenced by climate and climate change in ways independent of any immediate concerns of the energy sector. Satisfying future demands will require consideration of those factors, and more, of climate change, and of emissions mitigation policies and practices, perhaps as promulgated through any future international accords.

The information requirements of energy sector decision makers are not homogenous, nor are those of managers among energy users, all of whom may be concerned about the possible consequences of climate change for their energy resources, production, and demand. Energy users need to understand the background to their current demand, including any climate-driven factors, should those demands not be met or are threatened, and how all factors, not least climate change, will affect those demands, and their capacity to deliver in the future. The entire matrix of information demand is complex and, to a certain extent, geographically, geopolitically, and sector specific.

Table ES.6. Hydro-meteorological and Climate Data Needs

Location-specific information	Site-specific for raw material production
	Route-specific for raw material delivery
	Site-specific for energy production
	Route-specific for energy delivery
	Area-specific for demand assessment
Information with the required temporal resolution, with highest frequencies required, say, for wind, wave, and hydro generation	
Appropriate hydro-meteorological/climate parameters for each specific application	
Precision and accuracy of hydro-meteorological/climate information to within prescribed tolerances (however, as discussed in Chapter 5, it may not be possible always for the information to meet those tolerances)	
Consistency between historical, current, and future hydro-meteorological/climate information to the extent possible between observations and predictions	
In some cases, hydro-meteorological/climate data in a form suitable for direct incorporation in energy sector simulation or prediction models, for example, for demand, pollution, or emissions modeling	
Access to and delivery of hydro-meteorological/climate information appropriate to requirements	

Source: Generated by authors.

For decision makers within the energy sector, nonexclusive hydro-meteorological/climate data needs include those areas shown in Table ES.6.

In many developing countries, weather and climate services remain below World Meteorological Organization (WMO) standards, and some continue to deteriorate. Historical records that are essential for back casting or re-analysis and to ground projections for different timeframes (from seasonal to centennial) are lacking or not accessible (for example, not digitized). Local skills and capacity need to be built to enable climate modeling, and interaction needs to be encouraged between scientists, modelers, policy makers, and practitioners in key sectors (for example, energy, water, agriculture and forestry, environment) to ensure data requirements are known and information can be used.

Near-Term Actions

While adaptation to these impacts is likely to involve a drawn out process requiring major investments and strategic decisions, some actions to help mainstream climate considerations into energy sector planning and management are available in the short term.

- **Support awareness and knowledge exchange:** Disseminate experience and learn from the increasing data and knowledge of climate impacts on the energy sector, and their management.
- **Undertake climate impacts needs assessment:** Quantify the impacts, and hence risks, and data and information needs through the energy life cycle to guide adaptation practice in any country.
- **Develop project screening tools:** Develop templates to screen individual energy projects for climate vulnerability and risks, either retrospectively or during project planning and implementation.
- **Develop adaptation standards for the energy sector:** Such standards should cover engineering matters and information requirements.

- **Revisit planning timeframes and the use of historic data for future investments:** Traditional planning approaches that use historic data may need to be revisited an adjusted to reflect anticipated climate trends.
- **Assess potential climate impacts when retrofitting existing infrastructure:** Already available methodologies, such as energy or environmental audits, can help identify any needed changes in operational and maintenance protocols, structural changes and/ or the relocation of existing plants.
- **Implement specific adaptation measures:** Adaptation measures can include a range of off-the-shelf and innovative solutions that require investment in pilot or demonstration projects to illustrate the costs and benefits of alternative adaptation strategies; and subsequent support to integrate results into large scale operations. They also require expansion of the knowledge base.
- **Identify policy instruments:** They are needed to support climate impact management.
- **Support capacity building:** Increase the capacity of key stakeholders including energy sector policy makers, regulators, and operators, for climate risk management.

Notes

1. This is the case, for example, with some renewable energy sources—such as hydropower and wind power—in which investment decisions have an intrinsic uncertainty related to climate conditions.
2. In the climate change context, external benefits in terms of mitigation can be an interesting option for adaptation policies.
3. Many studies investigate the relationship between energy and climate, but without focusing on global climate change.
4. This is the case, for example, with some renewable energy sources—such as hydropower and wind power—in which investment decisions have an intrinsic uncertainty related to climate conditions.
5. In the climate change context, external benefits in terms of mitigation can be an interesting option for adaptation policies.
6. Thawing is likely to benefit some activities (for example, construction, transport, and agriculture) after it is completed, but the transitional period of decades or longer is likely to bring many disruptions and few benefits. Building infrastructure on permafrost zones can incur a significant cost because it requires that structures be stabilized in permanently frozen ground below the active layer, and that they limit their heat transfer to the ground, usually by elevating them on piles. For example, to prevent thawing of permafrost from the transport of heated oil in the Trans-Alaska pipeline, 400 miles of pipeline were elevated on thermosyphon piles (to keep the ground frozen), at an additional cost of US$800 million. The pipeline was completed at a cost of US$7 billion because of ice-rich permafrost along the route. This figure is eight times the estimated cost of installing the traditional in-ground pipeline (Parson et al., 2001).
7. Hallegatte (2006, 2008) casts some doubts on the optimality of such measures given the high level of uncertainty associated with forecasts of future climate conditions. She notes that according to some studies (Emanuel, 2005; Webster et al., 2005), the current high-activity level in the North Atlantic arises from climate change; whereas others such as Landsea (2005) argue that it arises from multi-decadal variability. Thus, adopting land-use restriction measures in this case could result in unacceptable costs once scientific uncertainty is resolved. But, given that this scientific debate will take decades to be solved and waiting is not a good option, she suggests decisions should be based on scenario analysis and the most robust solution, that is, the most insensitive to future climate conditions should be chosen (Lempert and Collins, 2007).
8. However, both are immature processes that receive far less research attention and funding than climate change science itself, and both have been examined mostly in areas such as health (for example, malaria) and agriculture (for example crop growth).

Acronyms and Abbreviations

AO	Arctic Oscillation
AAO	Antarctic Oscillation
ADB	Asian Development Bank
AOGCM	Atmosphere-Ocean General Circulation Model
AR4	Fourth Assessment Report (of the IPCC)
AFRETEP	African Renewable Energy Technology Platform
AU$	Australian dollars
°C	degrees Celsius
$°Cdec^{-1}$	degrees Celsius per decade
CCS	Carbon capture and storage
$CCSM_3$	Community climate system model
CDD	Consecutive dry days
CDP	Carbon Disclosure Project
CFE	National electric utility, Mexico
CH_4	Methane
CMIP3	Coupled Model Inter-comparison Project 3
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Conference of Parties
CSP	Concentrated solar power
CRA	Climate risk assessment
CRM	Climate risk management
CSIRO	Commonwealth Scientific and Industrial Research Organization
DESERTEC	DESERTEC Foundation "Clean Power from Deserts"
DJF	December, January, February
EACC	Economics of adaptation to climate change
ECMWF	European Centre for Medium-Range Weather Forecasts
EDF	Electricite De France
EIA	Environmental impacts assessment
ENSO	El Niño-Southern Oscillation
ERA-40	ECMWF 45 year reanalysis of the global atmosphere and surface conditions 1957-2002
ESMAP	Energy Sector Management Assistance Program
EUMETNET	European National Meteorological services
GCM	General Circulation Model
GCOS	Global climate observing system
GDP	Gross domestic product
GEF	Global Environment Facility
GET-CCA	Global Expert Team on Climate Change Adaptation (of the World Bank)
GFCS	Global Framework for Climate Services
GHG	Greenhouse gas

GPI	Genesis Potential index
$GTCO_{2eq}$	Giga tonnes of carbon dioxide equivalent
GTS	Global Telecommunication System
H_2O	Water
HEAT	Hands-on Energy Adaptation Toolkit
HDD	Heating degree days
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
IFC	International Finance Corporation
IFRC	International Federation of Red Cross
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Association
JJA	June, July, August
KESH	Korporata Energjitike Shqiptare, Albania Electricity Corporation
Km^2	Square kilometers
kW	Kilowatt
kWh	Kilowatt-hour
LDCF	Least Developed Countries Fund
LHPP	Large hydropower
LPG	Liquefied petroleum gas
m	meter
mm/yr	millimeter per year
$mm.year^{-1}$	millimeter per year
m/s	meters per second
ms^{-1}	meters per second
m^{-3}/year	cubic meters per year
MMA	March, April, May
MRI	Meteorological Research Institute, Japan
MW	Megawatt
NAO	North Atlantic Oscillation
NAM	Northern Annular Mode
NAPA	National adaptation plan of action
NATO	North Atlantic Treaty Organization
NCEP/NCAR	40-year reanalysis project, NOAA
NCS	National Climate Service
NGO	Nongovernmental organization
NMHS	National Meteorological and Hydrological Services
NOOA	National Oceanic and Atmospheric Administration
NPP	Net Primary Production
NSW	New South Wales
O_3	Ozone
OECD	Organization for Economic Co-operation and Development
PNA	Pacific North American Pattern

PRECIS	Regional climate modeling system, UK Met Office
PV	Photovoltaic
R&D	Research and development
RCM	Regional climate model
RCOF	Regional Climate Outlook Forum
RFF-PI	Resources for the Future—Policy Instruments
RSA	RSA Insurance Group, Munich
RX5D	Yearly maximum precipitation in five consecutive days
SAM	Southern Annular Mode
SCCF	Special Climate Change Fund
SHPP	Small hydropower
SO_2	Sulfur dioxide
SON	September, October, November
SRES	Special report on emissions scenarios, IPCC
TAR	Third Assessment Report (of the IPCC)
UFRJ	Federal University of Rio de Janeiro
UK	United Kingdom
UKCIP	United Kingdom Climate Impacts Programme
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNFCCCNWP	UNFCCC Nairobi Work Programme
UNIDO	United Nations Industrial Development Organization
UNWTO	World Tourism Organization
US	United States
USA	United States of America
US$	United States Dollar
WBG	World Bank Group
WCC-3	World Climate Conference - 3
WCRP	World Climate Research Programme
WCSS	World Climate Services Systems
WFP	World Food Program
WHO	World Health Organization
$W\ m^{-2}$	Watts per square meter
WMO	World Meteorological Organization
WRMA	Weather Risk Management Association
WRMF	Weather Risk Management Facility
%	percentage

World Bank Countries and Regions

For this report the authors focused on the regional country groupings of the World Bank Group.

East Asia & Pacific	American Samoa Cambodia China Fiji Indonesia Kiribati	Korea, Dem. Rep. Lao PDR Malaysia Marshall Islands Micronesia, Fed. Sts. Mongolia	Myanmar Palau Papua New Guinea Philippines Samoa Solomon Islands	Thailand Timor-Leste Tonga Vanuatu Vietnam
Europe & Central Asia	Albania Armenia Azerbaijan Belarus Bosnia and Herzegovina Bulgaria Croatia Czech Republic	Estonia Georgia Hungary Kazakhstan Kosovo Kyrgyz Republic Latvia Lithuania	FYR Macedonia Moldova Montenegro Poland Romania Russian Federation Serbia Slovak Republic	Slovenia Tajikistan Turkey Turkmenistan Ukraine Uzbekistan EU member states
Latin America & Caribbean	Argentina Belize Bolivia Brazil Chile Colombia Costa Rica Cuba	Dominica Dominican Republic Ecuador El Salvador Grenada Guatemala Guyana Haiti	Honduras Jamaica Mexico Nicaragua Panama Paraguay Peru	St. Kitts and Nevis St. Lucia St. Vincent & the Grenadines Suriname Uruguay Venezuela, RB
Middle East & North Africa	Algeria Djibouti Egypt, Arab Rep.	Iran, Islamic Rep. Iraq Jordan Lebanon	Libya Morocco Syrian Arab Republic Tunisia	West Bank and Gaza Yemen, Rep.
South Asia	Afghanistan Bangladesh	Bhutan India	Maldives Nepal	Pakistan Sri Lanka
Sub-Saharan Africa	Angola Benin Botswana Burkina Faso Burundi Cameroon Cape Verde Central African Republic Chad Comoros Congo, Dem. Rep. Congo, Rep.	Côte d'Ivoire Eritrea Ethiopia Gabon Gambia, The Ghana Guinea Guinea-Bissau Kenya Lesotho Liberia Madagascar	Malawi Mali Mauritania Mauritius Mayotte Mozambique Namibia Niger Nigeria Rwanda São Tomé and Principe Senegal	Seychelles Sierra Leone Somalia South Africa Sudan Swaziland Tanzania Togo Uganda Zambia Zimbabwe

Source: World Bank, 2010d.

CHAPTER 1

Overview

The climate is changing as a result of anthropogenic emissions of greenhouse gases (GHGs) that are now estimated to surpass the worst-case emission trajectory drawn under the IPCC in its third assessment report (IPCC, 2001a). Today 70 percent of these emissions come from fossil fuel combustion for electricity generation, in industry, buildings, and transport—and these emissions are projected to rise. By 2050, the global population will grow to 9 billion, with growth mostly concentrated in developing countries, and a large share will have a higher standard of living. If we continue along the current emissions path, delivering energy services and sustaining economic growth will result in a tripling of annual greenhouse gas emissions (World Bank, 2009a).

This highlights the urgency of taking actions to control emissions. It also highlights the need to adapt to unavoidable climate consequences from the damage already induced in the biosphere. By 2050, we will see increased weather variability and more frequent and extreme weather events, even if global GHG emissions are stabilized at 2°C above pre-industrial levels. These changes can affect energy resources and supplies as well as seasonal demand for energy services. In 2005 alone climate extremes accounted for a 13 percent variation in energy productivity in developing countries (World Bank, 2009a).

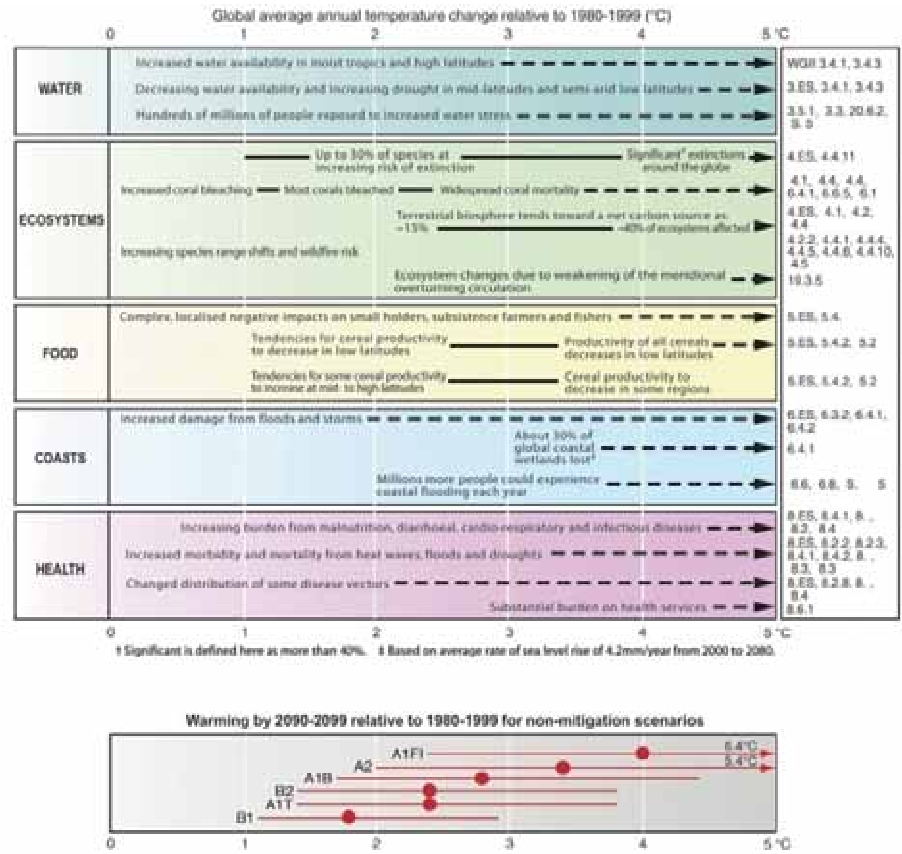
Given the intergenerational character of energy planning decisions, the long life span of energy infrastructure—15 to 40 years for power plants and 40 to 75 years for transmission lines—and the expected rise in energy demand, it is important to understand potential vulnerabilities and stresses on energy services due to climate consequences. This can support future planning and sustainable consumption patterns and avoid investments in energy systems that are maladapted to climate change and carbon intensive.

Climate Trends and Impacts on Energy Systems

Observations and general circulation models of climate trends indicate that all regions of the world will see increased warming, and this will be particularly marked in polar areas and mountainous regions. Coastal areas will experience sea level rise. By 2050, we will see higher temperatures and sea levels, changes in sea surface conditions and coastal water quality, increased weather variability, and more frequent and extreme weather events, even if global GHG emissions are stabilized at 2°C above pre-industrial levels. Already the entire energy supply chain is significantly vulnerable to climate variability and extreme events that can affect energy resources and supplies as well as seasonal demand; the projected changes will increase this vulnerability, and thus the need to adapt to changing conditions.

Figure 1.1, taken from the IPCC AR4, presents a generalized summary of anticipated climate change impacts as temperature rises. This representation shows the pervasive

Figure 1.1. Generalized Summary of Anticipated Climate Change Impacts as Temperature Rises



Source: IPCC, 2007d.

character of climate impacts on key sectors, including water availability, an important resource for the energy sector. Water crises in Uzbekistan, for example, are cited as the principal barrier to energy security for the republic, as thermal power plants require large volumes of water for cooling (UNDP, 2007).

For the energy sector in particular, the impacts of current and anticipated climate trends are substantial, threatening energy security and access, through, for example: changing the timing and volume of energy demand as temperatures rise; impacting hydropower generation capacity and the efficiency of thermal and nuclear power facilities that depend on significant volumes of cooling water; and challenging the integrity and efficiency of power transmission. Energy supply in low-income countries is particularly vulnerable due to their higher dependence on, and variability of, hydroelectricity and biomass energy supplies[1] and highly variable rainfall patterns (Chapter 3, "Indicators of Energy Sector Vulnerability," and Figure 3.5). At the same time, new economic opportunities could open up, such as greater access to resource-rich areas in the arctic due to melting sea ice and extended navigation seasons. Renewable energy potential could also increase (for example, solar, wind).

Addressing Climate Vulnerability

Energy infrastructure will be affected differently by climate change, depending on its location and the type of asset. Vulnerability is also driven by past practices that may exacerbate the potential for damage. Further, the degree to which this vulnerability affects a region's economy is driven by the adaptive or coping capacity.

From an adaptation perspective, the key questions for energy planners, regulators, and industry are: how vulnerable are their assets? What options do they have to increase their resilience to climate threats? How can future investments be adapted to anticipated changes?

Table 1.1 provides examples of generalized options to strengthen climate resilience in the energy sector. It shows the potential for major climate-driven disruptions as well as options to manage these impacts. Adaptation requires the involvement of many stakeholders engaged in energy planning, decision making, and investment to look at development goals and climate action on a longer time scale than normal planning processes. It also requires cross-sector and regional coordination to integrate considerations and solutions that span energy, water, agriculture, and hydro-meteorological services or cross traditional boundaries.

Table 1.1 Examples of General Options Available For Energy Sector Adaptation to Climate Change

Climate change	Impact	Possible adaptation action	Main actors
Average temperature rise	Increased demand for cooling, reduced demand for heating	Increase regional electric power generation capacity (A/C normally powered by electricity); plan for and implement enhanced delivery capacity; take into account changing patterns of demand (summer–winter, wet—dry season, north–south) when planning facilities (Resources for Future—Policy Instruments, RFF-PI)	National government Private sector
		Research and development (R&D) to make space cooling and building envelopes more efficient and affordable; build partnership with R&D centers	National government
		Lead by example—government agencies can weatherize buildings and manage energy use to reduce cooling demands	National and local (city) governments
	More frequent and/or longer heat waves	Ensure that energy requirements of especially vulnerable populations are met, especially during heat waves	Local governments
		Improve efficiency of energy use, especially electricity use at home and in commercial buildings, for example: energy audits, adequate tariff setting; contingency planning for probable seasonal electricity supply outages	National government Individuals
		Address vulnerability to heat waves in transmission and delivery systems	
	Increases in ambient temperature reduce efficiencies and generating capacity of power plants	Improve efficiency of power generation and delivery	National government Private sector
		Provide government incentives to study the issue of whether decentralized power production reduces risk (RFF-PI)	

(continued)

Table 1.1 (continued)

Climate change	Impact	Possible adaptation action	Main actors
Changes in precipitation/ water availability	Changes in precipitation/ water availability	Develop electric power generation strategies that are less water-consuming, especially for thermal power plant cooling, for example, dry cooling and increased cycles of concentration for cooling water; contingency planning for reduced hydropower generation, especially in regions dependent on snowmelt	National government Private sector
		Accelerate development of low-energy desalination technologies; higher cycles of concentration in cooling water systems (RFF-PI)	National government Private sector
		Diversify energy sources to provide a more robust portfolio of options	
		Establish incentives for water conservation in energy systems, including technology development and for integrated water and energy conservation planning	
Changes in intensity, timing, and location of extreme weather events	Disruption of energy conversion and generation —includes oil and gas platforms and undersea pipelines (RFF-PI)	Harden infrastructures to withstand increased flood, wind, lightning and other storm-related stress; consider relocation of infrastructures to less vulnerable regions in longer term (see Sea level rise column)	National government Private sector
		Increase resilience to energy interruptions and other threats; expand redundancy in electricity transmission capacity and fuel storage capacity	National government Private sector
	Disruption of energy transmission and transportation	Assess regional energy sector vulnerability and communicate vulnerabilities; advocate responsible contingency planning	
		Prepare for supply interruptions, for example, backup systems for emergency facilities, schools, etc.	National and local governments Private sector
Sea level rise	Risks to infrastructures in vulnerable coastal areas	Conduct regional analysis of vulnerability of coastal energy infrastructure to sea level rise; advocate responsible land-use planning and contingency planning	National and local governments Private sector

Source: Adapted from National Academy of Sciences, Courtesy of National Academics Press, 2010.

The large diversity of energy needs and supply options in developing regions, coupled with varying degrees of exposure to climate change, implies that generalized recommendations are not possible. For example, in those countries with high reliance on biomass, it is clear that energy planning should focus strongly on identifying how climate is likely to affect yields and on developing strategies to cope with shifting patterns of precipitation and crop yield. Regions with coastal assets will need to focus on reducing vulnerability to weather extremes and sea level rise. Others, where hydropower is prevalent, will need to address impacts from changes in rainfall cycles. The increased likelihood of extreme weather events implies that contingency plans are required, increasing firm energy availability, extending backup power capacity, and extending disaster protection and recovery plans. Finally, in a world of heightened uncertainty of the effects of changing climate and energy security in general, an overall drive toward increased diversity of energy demand and supply options would seem to be an element of improved climate resilience.

To develop flexible adaptation strategies for existing and planned assets, governments and utilities will additionally need access to tailored and timely weather information. The availability of such information raises a further challenge.

Structure of This Report

This report summarizes the latest available information on climate impacts on energy systems. It draws on available peer-reviewed literature, going beyond the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The report has the following chapters and scope:

Chapter 1: Overview

Chapter 2: Observed and Expected Climate Change focuses on observed and projected trends for parameters of relevance to the energy sector. It identifies "hotspots" (areas with large inter-annual variability) for World Bank geographic regions.

Chapter 3: Climate Impacts on Energy identifies climate vulnerabilities in the energy sector, including energy resource endowments, supply, infrastructure, transportation, and use.

Chapter 4: Emerging Adaptation Practices highlights adaptation issues relevant to energy sector impacts from climate change, including no-regret actions, existing inefficiencies, cross-sector adaptation, and the role of public institutions.

Chapter 5: Weather and Climate Information discusses the required and available weather and climate information to support energy sector adaptation to climate change.

Chapter 6: Climate Resilience explores the desirable outcomes of adaptation decisions and strategies, and the main gaps and options for integrating climate risk considerations into energy systems.

Chapter 7: Near-term Actions to Support Adaptation identifies potential near-term measures to support the integration of climate considerations into impacts assessment and planning processes, and supporting information and data needs.

This report is supported by a Glossary and References and the following Appendixes:

Appendix A: IPCC Emissions Scenarios and Confidence Levels

Appendix B: Re-analyses and General Circulation Models

Appendix C: Observed Trends in Precipitation and Sea Level Change

Appendix D: Projected Temperature and Precipitation Changes in Different Regions

Appendix E: Icing and Hail

Appendix F: Electric Utilities Adapt Their Practices to Respond to Natural Disasters

Appendix G: Locally Tailored Adaptation Options: An Example

Appendix H: Adapting to Climate Change on Mexico's Gulf Coast

Appendix I: Case Study: Regulation for the Aviation Industry

Appendix J: Access to Predictions

Appendix K: Frameworks, Methodologies, and Tools for Climate Risk Management and Decision Making Under Uncertainty

Appendix L: National and Regional Adaptation Initiatives

Appendix M: Global Framework for Climate Services

Note

1. Note: the use of renewable energy is not necessarily an indicator of vulnerability.

CHAPTER 2

Observed and Expected Climate Change

Climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems
(White House Task Force on America's Climate Choices, 2010).

Long-term climate change and its impacts on weather variability (and extremes) will impact energy resources, their production, and use, and affect strategies for adaptation. Some impacts may be systemic. For example, changes in mountain hydrology will affect the firm energy of an entire hydropower system over a large geographical area. Others may be localized, such as impacts of extreme weather events on energy infrastructure in low-lying coastal areas.

Here we introduce climate parameters and characteristics that appear to be of particular relevance to the energy sector. We summarize current scientific knowledge of observed and expected changes in these parameters. The information presented in this chapter provides a frame of reference for subsequent chapters.

Climatic Impacts on Energy Services

For adaptation to climate change to be effective, it is vital to be aware of how the current (or past) climate impacts the energy sector in addition to understanding projected changes. For example:

- An increase in temperature reduces the need for heating and enhances the need for cooling.
- An increase in precipitation generally increases water availability for cooling purposes as well as for hydropower production.
- A decrease in precipitation increases the competition for water resources, both locally and remotely, as water supply may be routed thousands of kilometers via rivers, aqueducts, and so forth. Larger decreases (droughts) are often accompanied by reduced cloud cover, with positive implications for solar energy production.
- Highly variable water supply due to flooding or drought may have severe implications for infrastructure itself, including water regulation (storage), safeguarding, and maintenance—in addition to the issues related to energy demand and supply.
- Accessibility to remote water resources such as mountain glaciers or cold region snowmelt and water bodies (particularly in permafrost regions) will alter with

changes in temperature and precipitation. Most likely this will be noted as first offering better access, during the period of rapid glacier retreat, and later with the potential loss of an annual buffer (glaciers), offering reduced or constrained access with present infrastructure.

- A change in cloud cover influences solar energy production.
- Changes in wind direction, frequency, and strength affect wind power production, either adversely or positively.
- The occurrence of extreme events associated with tropical storms (for example, hurricanes, but not exclusively) may cause damage to infrastructure.
- Coastal structures are influenced by sea level rise, and with a higher sea level, the need for adaptation options will often require extra energy supply; for example, where major rivers meet the ocean, additional pumping facilities could be required.

These concerns should be kept in mind. Although for electricity generation the sector makes varied use of available climate information to plan for peak load management and extreme event response, in many parts of the world the exact vulnerability to weather variations is not well mapped, even without taking global climate change into account. Changes in variability would generally increase operation and maintenance costs of energy delivering systems. In essence, many countries still have to assess current weather variability in quantitative terms to cope with immediate problems. This can be illustrated by some past extreme climatic events that have caused serious disruptions in energy production and delivery. The European heat wave in 2003 led to very low river flows and increased water temperature and had consequences on the cooling of power stations and peak power demands: in some cases power production was reduced, in others legal exemptions were sought to allow water at higher temperature to be returned to rivers after it was used to cool power production units (Dubus, 2010). In 2005 exposed infrastructure, such as electricity transmission networks, was especially vulnerable to the effects of Hurricane Katrina. And, in Siberia and Arctic Russia, the stability of oil pipelines and electricity transmission networks has been impacted in recent years by warming in permafrost areas. Emerging climate conditions and trends will change the frequency and severity of weather events. They will require a thorough rethinking of energy planning, construction, operations, and maintenance to better identify and manage climate risks now and in the future.

This chapter focuses on major climate trends and the threats or risks these pose. It does not focus on climate variability; that is, it concentrates on long-term trends that are most relevant for energy infrastructure planning and operation (strategic decisions). Varying meteorological factors have a strong influence on many aspects of the life cycle of energy generation and use. This chapter deals with the more obvious meteorological variables, such as (near-) surface temperature and precipitation, as well as sea level, wind, and solar radiation and their statistical features, such as extremes.[1] Derived quantities such as heating/cooling degree days, permafrost extent, and sea ice cover play important roles as well.

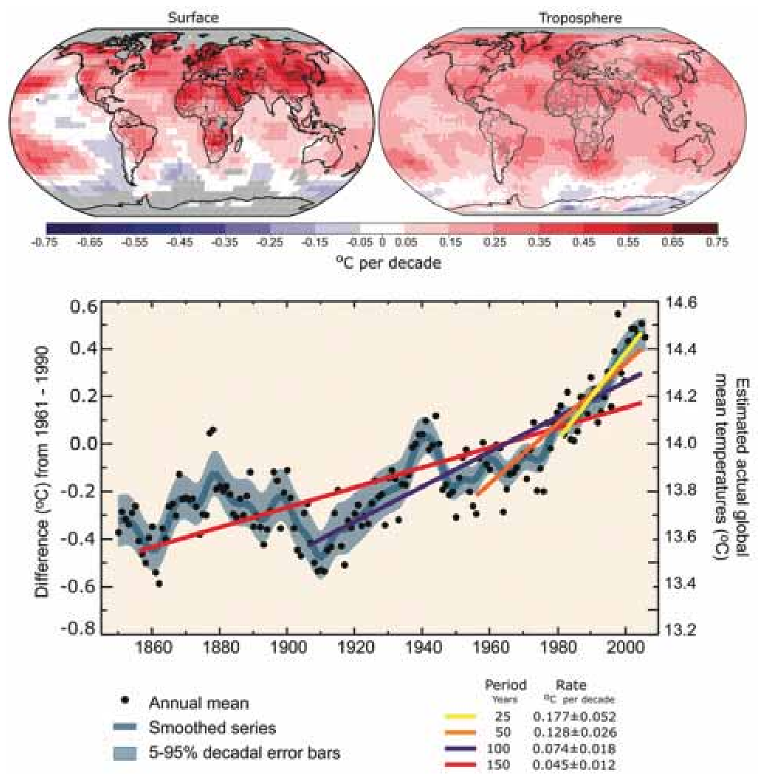
Although operational (tactical) decisions are also very much impacted by climate change, these can be tackled after assessing overall climatic conditions by employing available weather and climatic tools (for example, seasonal forecasts). A thorough discussion of the tools available for operational purposes and their practical use is presented in Chapter 5. Regional climate scenarios, while of critical importance for managing energy supply and demand, remain highly uncertain and are included only in a limited way.

Recent Observed Climate Change

The best available (global) baseline over which to assess future climate changes is the observed climate in the recent past. "*Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases*" (IPCC, 2007a). Globally, the IPCC reports 765 significant observed changes in physical variables, with 94 percent of these changes consistent with warming. In biological terms, scientists report 28,671 significant observed changes, 90 percent of which are consistent with the hypothesis of global warming (IPCC, 2007d). From this evidence, the following general assertions are made:

- The *global average surface temperature* has increased, especially since about 1950. The total temperature increase from 1850–1899 to 2001–2005 is 0.76°C ± 0.19°C (IPCC, 2007a). The rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) is nearly twice that for the last 100 years (Figure 2.1).

Figure 2.1. (Top) Patterns of Linear Global Temperature Trends over the Period 1979 to 2005



Source: IPCC, 2007a.
Note: Estimated at the surface (left), and for the troposphere from satellite records (right). Gray indicates areas with incomplete data. (Bottom) Annual global mean temperatures (black dots) with linear fits to the data. The left-hand axis shows temperature anomalies relative to the 1961 to 1990 average and the right-hand axis shows estimated actual temperatures, both in °C. Linear trends are shown for the last 25 (yellow), 50 (orange), 100 (magenta), and 150 years (red). The smooth blue curve shows decadal variations, with the decadal 90 percent error range shown as a pale blue band about that line. The total temperature increase from the period 1850 to 1899 to the period 2001 to 2005 is 0.76°C ± 0.19°C.

- There is very high confidence (Appendix A) that recent warming is strongly affecting *terrestrial biological systems*. Based on satellite observations since the early 1980s, there is high confidence that there has been a trend in many regions toward earlier greening of vegetation in the spring linked to longer thermal growing seasons due to recent warming.
- There is high confidence that *natural systems related to snow, ice, and frozen ground* (including permafrost) are affected. Examples are: (i) enlargement and increased numbers of glacial lakes; (ii) increasing ground instability in permafrost regions and rock avalanches in mountain regions; (iii) reduced volume and surface extension of tropical glaciers.
- There is high confidence that *hydrological systems* are being affected: increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers, and warming of lakes and rivers in many regions, with effects on thermal structure and water quality (Appendix C).
- Some *extreme* weather events have changed in frequency and/or intensity over the last 50 years: It is very likely that cold days, cold nights, and frosts have become less frequent over most land areas, while hot days and hot nights have become more frequent. It is likely that heat waves have become more frequent over most land areas. It is likely that the frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas. It is also likely that the incidence of extreme high sea level has increased at a broad range of sites worldwide since 1975.
- A tendency for a poleward displacement of the mid-latitude *storm tracks* has been observed. This implies a modest change in the wind climate in the regions influenced, with slight reduction of the westerlies equator-wards and increase polewards within the storm track.
- There is observational evidence of an increase in intense *tropical cyclone activity* in the North Atlantic since about 1970, and suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. However, multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. The confidence in a more general statement about overall change is therefore not high, even more so if specific smaller regions are to be assessed.
- There is emerging evidence of increase variability of climate parameters (temperature, precipitation, extreme events). This is supported by the observed trends in storm intensification, increased frequency of extreme events, and above-record temperatures.
- The melting of ice sheets, glaciers, and ice caps has accelerated. A wide array of satellite and ice measurements now demonstrate beyond doubt that both the Greenland and Antarctic ice sheets are losing mass at an increasing rate. Melting of glaciers and ice caps in other parts of the world has also accelerated since 1990.
- Globally, *sea levels have risen* an average of 18 cm since the late 19th century. Current sea level rise is underestimated: Satellite data show global average sea level rise (3.4 mm/yr over the past 15 years) to be 80 percent above past IPCC predictions. This acceleration in sea level rise is consistent with a doubling in

contribution from melting of glaciers, ice caps, and the Greenland and West Antarctic ice sheets.

Though direct observations provide the optimum picture of the climate (Appendix C), re-analyses[2] can offer an alternate and effective instrument to review recent global climate trends,[3] especially when a full set of direct observations is not available (see Appendix B). Results from two re-analyses[4] are explored below and are based on the most recent 30-year averages (1970−1999) due to their overlap with Coupled Model Inter-comparison Project 3 (CMIP3) climate model runs of the 20th century:

- NCEP/NCAR (Kalnay et al., 1996, with continuous updates to their system)
- ERA-40 (Uppala et al., 2005)

These re-analyses allow some insight into the stationary nature of the observed climate and inter- and intra-annual variations of climate parameters. The limits of re-analyses are discussed in Appendix B.

How Stationary Has the Climate Been?

Climate has never been stationary; however, the issue is not of stability but of drastic change over a relatively short period of time, when compared with the historical record. Linear trends offer an immediate way to assess how stationary the climate is. Table 2.1 shows the trend of four variables relevant to the energy sector.

- **2-meter temperature** has increased about 0.15°C per decade globally, confirming this well-documented trend (for example, Solomon et al., 2007).
- **Global solar radiation at the surface** has increased about 1.5 W m^{-2} over 30 years (commensurate with the lifetime of a solar power station), accounting for a small percentage of the globally averaged 190 W m^{-2} global radiation. The re-analyses show some discrepancy for solar radiation, but the sign of the trends is consistent (positive over land, negative globally).
- **10-meter wind speed and 850-hPa wind** trends are small compared to their global averages (3.2 m s^{-1} at 10-m, 4.8 m s^{-1} at 850-hPa) despite latest observations showing regional decreases in wind. Guo et al. (2010) found that "the averaged rate of decrease in annual mean wind speed over China is −0.018 $ms^{-1}a^{-1}$," and stated that "this decrease in strong winds also may lower the potential for wind energy harvest in China." The trends for 10-m and 850-hPa winds on a global scale need not be consistent: for instance, changes in the 10-m wind can be affected by changes in the roughness of the surface (for example, growing/removed vegetation).

Table 2.1. Global Linear Trends over Land (Both Land and Oceans in Parenthesis) for the 30-Year Period 1970−1999

Model	2-Meter T (°°C dec^{-1})	Solar Radiation (W m^{-2} dec^{-1})	10-Meter Wind (m s^{-1} dec^{-1})	850-hPa Wind (m s^{-1} dec^{-1})
ERA-40	0.30 (0.17)	0.95 (–0.32)	–0.0018 (0.014)	–0.023 (0.009)
NCEP/NCAR	0.18 (0.13)	0.15 (–0.28)	0.019 (0.030)	–0.0053 (0.025)
Average trend	0.24 (0.15)	0.55 (–0.30)	0.0086 (0.022)	–0.014 (0.017)

Source: Generated by authors.
Note: "dec" stands for decade, that is, 10 years.

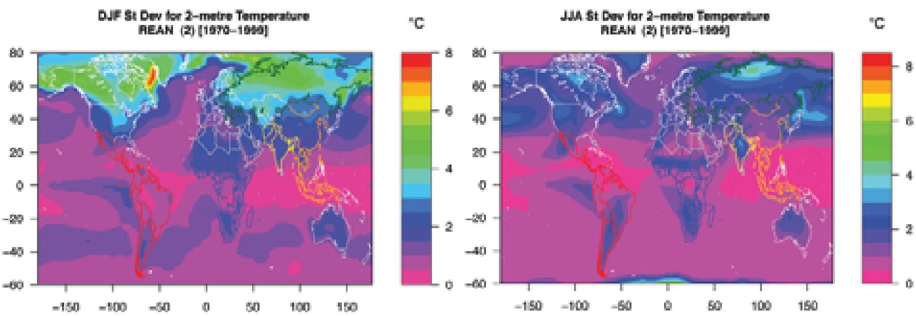
What Large Intra- and Inter-annual Variations Have Been Observed?

Intra- and inter-annual climate variations are important for energy planning and operations.

Figure 2.2 shows the standard deviation of 2-meter temperature for the two extreme seasons, December–January–February (DJF) and June–July–August (JJA). Europe and Central Asia is the only region with large inter-annual temperature variations; up to about 5°C in DJF. Here the energy industry is vulnerable to large temperature variations in areas covered in permafrost (Schuur et al., 2008). Pipelines may be at risk of accidents as a result of permafrost thawing, particularly when the ice content is high, as this process can lead to uneven soil settling, displacement of piles, "floating" of pipes, and pipeline deformation (Vlasova and Rakitina, 2010). Relatively large variations are also observed in JJA, the more crucial season for permafrost thawing.

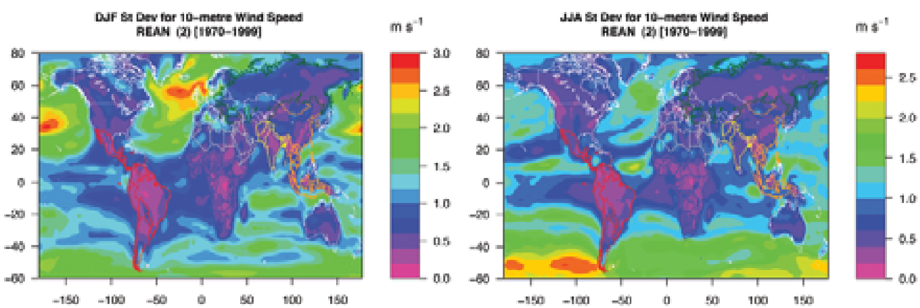
Figure 2.3 shows large deviations in near-surface wind speed over the oceans and, typically, during the colder season. This is critical for wind energy production, as well as the planning and operation of oil rigs (cyclones, storm surges), power transmission

Figure 2.2. Seasonal Standard Deviation of Two-Meter Temperature for DJF (Left) and JJA (Right) as an Average of the Two ERA-40 and NCEP/NCAR Re-analyses



Source: Generated by authors.
Note: Large deviations of in excess of 4°C are present particularly over Siberia, a region where permafrost is prevalent. Note that the six World Bank regions have been highlighted.

Figure 2.3. Seasonal Standard Deviation of Ten-Meter Wind Speed for DJF (Left) and JJA (Right) as an Average of the Two ERA-40 and NCEP/NCAR Re-analyses



Source: Generated by authors.
Note: Large deviations of around 2 m s-1 are present in the proximity of the Gulf of Mexico, especially in the DJF season.

and distribution (heavy winds), and fuel transportation, especially via sea (cyclones, storm surges). Offshore operations in the Gulf of Mexico are exposed, particularly in the DJF season. Large wind variations in northwest Africa may also become relevant for the DESERTEC[5] planning and operations.

Expected Climate Change

There is substantial evidence, most coherently outlined in the IPCC reports, that the current pace of climate change has no precedent in available geological records. While the political decision to address the consequences of climate is still in the making, the scientific literature is clear in that climate change is likely to pose a significant challenge to the goals of sustainable development as well as seriously impinge on the ability of key ecosystems to maintain their current levels of service.

The long-term trends behind global climate change are on top of natural multi-annual oscillations, which in the short term may mask the absolute net effects of global warming. Some of these oscillations do have some degree of predictability. For example, the strength of ENSO (El Niño-Southern Oscillation[6]) and its counterpart, La Niña, can be predicted with some anticipation based on measurements of the temperature dipoles in the Pacific Ocean in front of the coast of South America.

Predictions on a longer time scale, however, are generally not feasible, other than by reference to past events. In general, the consequences of different paths of global GHG emissions give the clearest signals for the far future, where anthropogenic forcing is the largest compared to the internal fluctuations of the climate system. Projections of climate define possible outcomes of the future climate pathways, but will not necessarily show the one that will actually be realized.

Physical climate change is normally viewed on a multi-decadal time scale, such that changes in statistical parameters can be estimated. The climate at a given time has traditionally been calculated from 30-year averages. Hence, estimates of the magnitude of climate change have normally consisted of comparisons of periods with several decades' separation.

This also poses a challenge for climate modeling. For example, a variable, say temperature, may be modified:

- only in its average value (for example, overall hotter, cooler);
- only in the shape of the distribution (for example, higher/lower extreme values); or
- as a combination of change in average value and shape (for example, overall hotter but fewer extremes).

As a consequence, there is no single statistical measure capable of indicating how a variable may change. Also, each variable may be affected by different modifications: thus, if variability in temperature increases, this is in general not followed by a proportional increase in, say, wind. Though many climate parameters are projected to change, only subsets of these are of direct and immediate relevance to the energy sector. Some of these are discussed below.

The discussion draws on IPCC AR4 projections and complements this with an analysis of projected inter-annual variability for climate projections under two different IPCC greenhouse gas emission scenarios (A2 and B1, Appendix A). Of the 25 climate models[7] that form part of the CMIP3 dataset prepared under the IPCC AR4, 15 are used for this analysis. A description of these models, together with caveats about the results, can be found in Appendix B.

Projected Changes in Surface Temperature

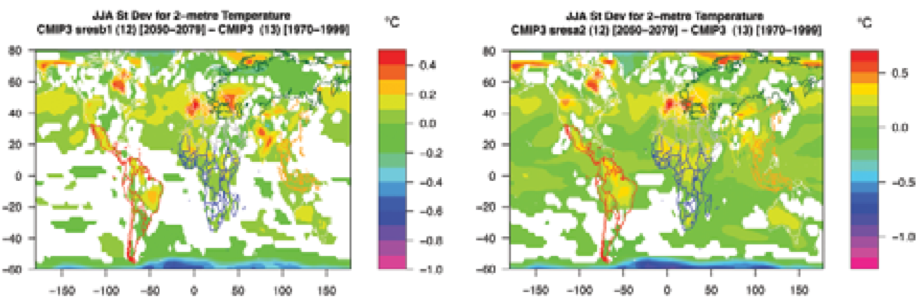
It is evident that all land regions are very likely to warm during the 21st century. Geographical patterns of projected warming of surface temperatures are scenario-independent, with the greatest temperature increases over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean, consistent with the observed changes during the latter part of 20th century, as well as over mountain regions. Appendix D provides detailed regional information for the likely changes in climate between the 1980 to 1999 period and the 2080 to 2099 period from a set of 21 global models in the multi-model data set for the A1B scenario for all geographic regions (IPCC 2007a, Chapters 10, 11).

To complement this, expected changes in inter-annual temperature variability are presented in Figure 2.4 based on an assessment of the standard deviation for the A2 and B1 scenarios. The western part of Europe and Central Asia, West Africa, and several parts of Latin America and the Caribbean are projected to experience increasing levels of temperature variability; in excess of 0.2°C in B1 and 0.4°C in A2.

Note the different color scales in Figure 2.4. These changes correspond to a projected variability of more than 10 percent when compared to the observed variability (see Figure 2.4, right), therefore adding additional strain to ecosystems, water resources, and energy systems and in general to all economic activities, including transport and agriculture. It would therefore appear sensible to put in place measures to manage this expected increased variability, notwithstanding the fact that current variability may already warrant attention.

The derived quantities of heating/cooling degree days (HDDs/CDDs) are closely related to temperature. These quantitative indices reflect the demand for energy to heat/

Figure 2.4. Projected Changes in the Standard Deviation of Two-Meter Temperature for JJA



Source: Generated by authors.
Note: Changes are computed as differences with respect to the 1970–1999 climate run results, for scenarios B1 (left) and A2 (right). White areas indicate near-zero differences. Numbers in parenthesis in the title indicate the number of models used for the averaging of each individual period (that is, before computing the differences). Note the different color scales in the two plots.

cool a home or business. One study including five regions in Australia and nine climate models (Wang et al., 2010) found potentially significant climate change impacts on heating/cooling energy requirements within the life span of existing housing stock. Such requirements could vary in the range of -26 to 101 percent by 2050 and -48 to 350 percent by 2100 given the A1B, A1FI, and 550 ppm stabilization emission scenarios, dependent on the existing regional climate.

Projected Changes in Wind Patterns

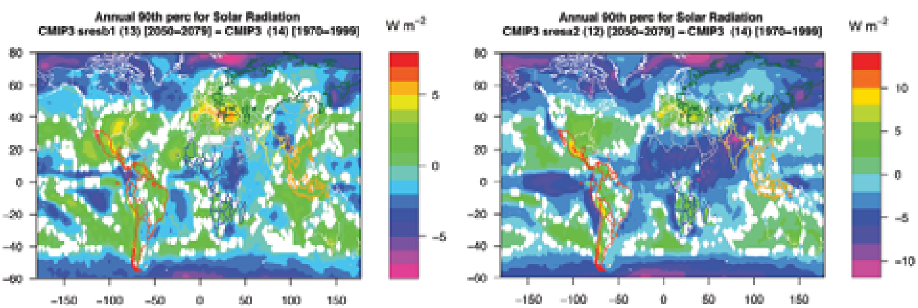
A primary forcing mechanism for generating winds in the mid-latitudes is the difference in temperature between polar and tropical air masses. In theory, the reduction of the thermal difference between polar regions and the tropics should reduce the mean mid-latitude wind speeds. Though wind trend studies in selected areas indicate that this may indeed be happening, there is some contradictory evidence of the impacts.

Projected Changes in Solar Radiation

Projected changes in the high-end extreme values of the distribution of global solar radiation (that is, 90th percentile) are discussed here. While changes in high-end extreme values need to be accompanied by other statistical measures (for example, changes in mean values), they can provide an indication of how peak solar energy production could vary under such projections.

Figure 2.5 shows that in the B1 scenario the intensity of these extreme values is likely to be reduced by about 5 W m^{-2} over sub-Saharan Africa (especially in the eastern part) but increased by more than 5 W m^{-2} over the Middle East. Such changes are more pronounced in the A2 scenario, with an additional negative pattern over India, and a reduction of about 10 W m^{-2}. Despite the projected reduction in solar radiation over the Sahara, that region is well suited for concentrated solar power (CSP) plants[8] nonetheless, as mean global radiation there is very high (see Figure 2.5, left).

Figure 2.5. Projected Changes for the 90th Percentile of the Annual Global Solar Radiation



Source: Generated by authors.
Note: Changes are computed as differences with respect to the 1970–1999 climate run results, for scenarios B1 (left) and A2 (right). White areas indicate near-zero differences. Numbers in parenthesis in the title indicate the number of models used for the averaging of each individual period (that is, before computing the differences). Note the different color scales in the two plots.

Projected Changes in Sea Level and Sea Ice

A recent report by Allison et al. (2009) synthesized the most policy-relevant climate science published since the IPCC AR4 report (note, however, that these findings have yet to be substantiated by the wider scientific community):

- Sea level rise associated with climate change should be analyzed through careful consideration of at least three factors and their interdependence: (i) ocean water thermal expansion and associated heat storage; (ii) the contribution of ice cap melting, particularly in Greenland and the Antarctic; and (iii) adjustment in sea surface elevations as result of isostatic earth crust adjustments and the associated changes in gravitational fields (forces).
- Summertime melting of Arctic sea ice has accelerated far beyond the expectations of climate models: the area of summertime sea ice during 2007–2009 was about 40 percent less than the average prediction from IPCC AR4 climate models (about 8 million km^2). According to Holland et al. (2006), the Arctic summer could become nearly ice-free by 2040.
- Sea level prediction revised: by 2100, global sea level is likely to rise at least twice as much as projected by Working Group 1 of the IPCC AR4 (the range was 18–59 cm); for unmitigated emissions it may well exceed 1 meter. However, the projected pattern of sea level changes is not very reliable and it is more practical to assume that the current pattern will persist. Note also that some areas have been experiencing a negative sea level change (for example, many parts of the western coast of Central and South America). Other parts are also affected by subsidence, and hence the current observed sea level increases may be due to this phenomenon.

Projected Changes in Permafrost

With the projected rise in Arctic land temperatures of several degrees during the 21st century (Chapman and Walsh, 2007), it is important to understand how permafrost cover could evolve. A particular concern is what may happen to permafrost that is currently found in near-surface soils, as this portion is most vulnerable to climate change and its degradation has the potential to initiate a number of feedbacks, predominantly positive, in the Arctic and in the global climate system (McGuire et al., 2006). Permafrost degradation and rising soil temperatures are at the heart of many of these potential feedbacks.

Earlier results by Lawrence and Slater (2005) indicated that the strong Arctic warming predicted in the Community Climate System Model[9] (CCSM3), one of the CMIP3[10] models, drives severe degradation of near-surface permafrost during the 21st century. More specifically, they showed that CCSM3 simulations of the spatial extent of present-day permafrost agree well with observational estimates—an area, excluding ice sheets, of 10.5 million km^2. By 2100 the model predicts that more than 90 percent of permanent permafrost surface will be lost, with as little as 1.0 million km^2 of near-surface permafrost remaining.

Although this estimate requires further testing and verification strong Arctic warming is enough to substantially reduce the total area of near-surface permafrost by 2100 in all climate models that incorporate this phenomena. Permafrost degradation of this magnitude is likely to invoke a number of [unspecified] hydrological, biogeochemical, and ecological feedbacks in the Arctic system (Lawrence et al. 2008), including the potential release of a considerable amount of methane (CH_4) that would provide a positive feedback to global warming. However, it is worth emphasizing that such processes are still highly uncertain, not least because observations are sparse (Krey et al. 2009).

Projected Changes in Rainfall

Climate projections using multi-model ensembles show increases of globally averaged mean water vapor, evaporation, and precipitation with global warming over the 21st century. The models indicate that precipitation generally increases at high latitudes in both winter and summer seasons, and in areas of regional tropical precipitation maxima (such as the monsoon regimes, and the tropical Pacific in particular), with general decreases in the subtropics.

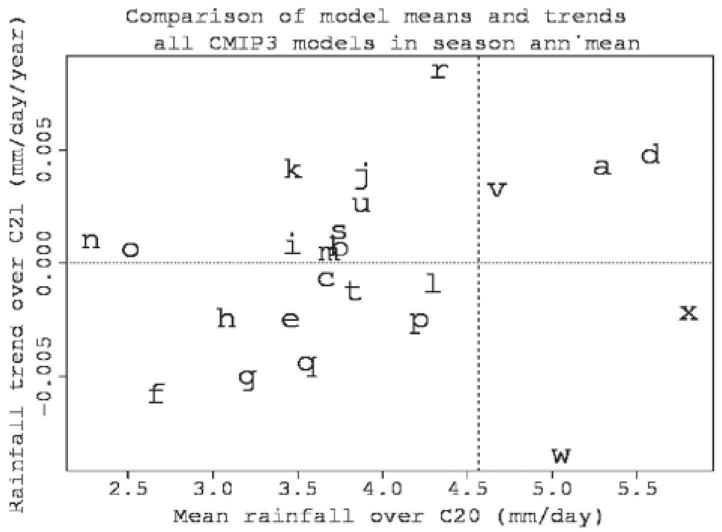
As shown in Appendix D, by the late 21st century under the A1B scenario, large increases in annual and winter precipitation exceeding 20 percent occur mostly at high latitudes. Increases in precipitation are consistently projected in models for East Africa and South Asia in summer and for the annual mean, and in East Asia and South East Asia increases are projected in winter, summer, as well as in the annual mean. Substantial precipitation decreases of up to 20 percent occur in southern Africa in winter and in the Mediterranean and Caribbean regions in summer. Decreases in precipitation also occur in the Sahara region in winter, in Central Asia in summer, and in Central America in winter, summer, and for the annual mean. However, it is uncertain how rainfall will evolve in the 21st century for a large number of regions and seasons, in particular in West Africa and South America in winter, summer, and for the annual mean, in Central Asia in winter and for the annual mean, as well as in South Asia in winter.

Taking the case of Africa, this means that there will be regions with a projected increase in precipitation, others with a decrease, and quite large areas where the models disagree so that at present it is not possible to make a reliable projection. This regional diversity has to be kept in mind. It also emphasizes that even when models largely agree on the sign of change, there may still be quite some doubt about the numerical value of the change. Figure 2.6, for example, illustrates this lack of consensus on rainfall trends for the northwest region of the Amazon for each of the general circulation models (GCMs) in the CIMP3 dataset, under the A1B scenario (Vergara and Scholtz, 2011). While some models indicate the likelihood of increased precipitation, others predict a net reduction.

Rainfall is not the only climate factor that has impacts on available water resources. Evaporation, soil moisture, and runoff and river discharge are also key factors. In climate models, global mean precipitation changes closely balance global evaporation changes, but this relationship does not hold locally because of changes in the atmospheric transport of water vapor. Over land, rainfall changes tend to be balanced by both evaporation and runoff.

Under the A1B scenario, the ensemble mean shows that runoff will be notably reduced in the Mediterranean region and increased in South East Asia and in high latitudes, where there is consistency among models in the sign of change. The larger changes reach 20 percent or more of the simulated 1980–1999 values, which range from 1 to 5 mm/day in wetter regions to below 0.2 mm/day in deserts. Flows in high-latitude rivers are projected to increase, while those from major rivers in the Middle East, Europe, and Central America tend to decrease.

Figure 2.6. Simulation of Mean Annual Rainfall in the 20th Century (X-Axis) and Rainfall Trend in the 21st Century (Y-Axis) in the Northwest Region of Amazonia



Source: Vergara and Scholtz, 2011.
Note: The vertical dotted line is the observed rainfall in the 20th century. The horizontal line assumes no change for the 21st century. The CMIP3 GCMs are labeled as in Table 2.2.

Table 2.2. GCMs in the CMIP3 Archive

Model identifier	Model name	Model identifier	Model name
a	bccr_bcm2.0	m	ingv_echam4
b	ccma_cgcm3_1	n	inmcm_3_0
c	ccma_cgcm3_1_t63	o	ipsl_cm4
d	cnrm_cm3	p	miroc3_2_hires
e	csiro_mk3.0	q	miroc3_2_medres
f	csiro_mk3.5	r	miub_echo_g
g	gfdl_cm2.0	s	mpi_echam5
h	gfdl_cm2.1	t	mri_cgcm2_3_2A
i	giss_aom	u	ncar_ccsm3_0
j	giss_model_e_h	v	ncar_pcm1
k	giss_model_e_r	w	ukmo_hadcm3
l	iap_fgoals1_0_g	x	ukmo_hadgem1

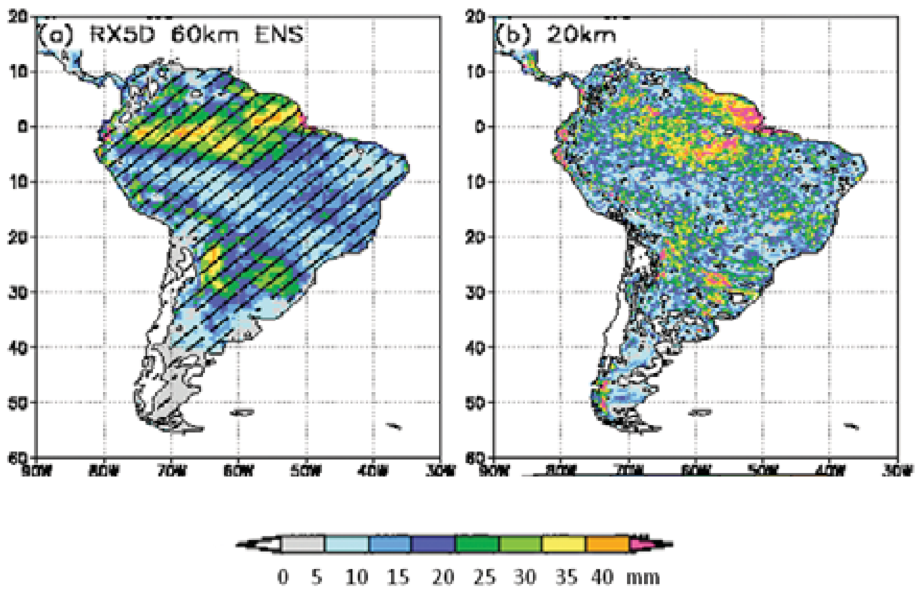
Source: Vergara and Scholtz, 2011.

Precipitation changes due to warming could lead to changes in the seasonality of river flows. In regions where winter precipitation currently falls as snow, spring flows may decrease because of the reduced or earlier snowmelt, and winter flows may increase. In many cases peak flows by the middle of the 21st century would occur at least a month earlier. In regions with little or no snowfall, changes in river flows depend much more on changes in rainfall rather than on changes in temperature and may have an enhanced probability of wintertime river flooding. The seasonality of flows in these regions will increase, often with higher flows in the peak flow period and either lower flows during the low-flow season or extended dry periods.

There is a wider consensus among models that global warming results in an intensification of the water cycle, with more intense periods of rainfall and the lengthening of dry periods. Most climate models project precipitation intensity increases almost everywhere, particularly in tropical and high-latitude areas that experience increases in mean precipitation. Models also project a tendency for drying in mid-continental areas during summer, indicating a greater risk of droughts in these regions. In a warmer climate, the model projected precipitation tends to concentrate in more intense events, with longer periods of little precipitation in between. Therefore, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods. It is also notable that, in relation to changes in mean precipitation, the wet extremes are projected to become more severe in many areas where mean precipitation increases, and dry extremes are projected to become more severe in areas where mean precipitation decreases.

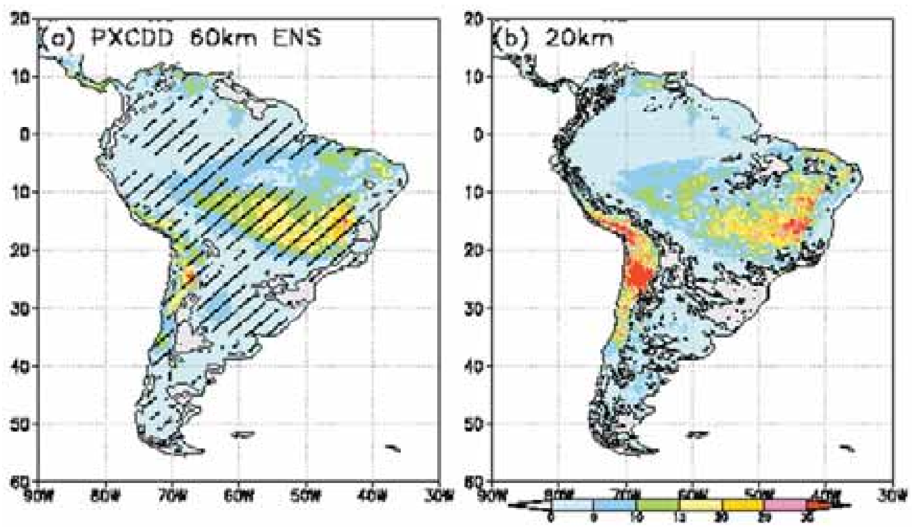
This intensification can be characterized using an index of intense rainfall (yearly maximum precipitation in five consecutive days, Rx5D) and one for consecutive dry days (CDDs). Both metrics are shown in Figures 2.7 and 2.8, for the South American continent, as projected by the GCM of the Meteorological Research Institute of Japan (MRI) with Earth Simulator for 60x60 and 20x20 km resolution under scenario A1B (Vergara and Scholz, 2011).

Figure 2.7. Changes in Maximum Five-Day Precipitation Total (mm) between the Present and the End of the 21st Century



Source: Vergara and Scholz, 2011.
Note: The panel on the left (a) is for 60 km and the panel on the right (b) is for 20 km.

Figure 2.8. Changes in Consecutive Dry Days Precipitation Total (mm) between the Present and the End of the 21st Century



Source: Vergara and Scholz, 2011.
Note: The panel on the left (a) is for 60 km and the panel on the right (b) is for 20 km.

Extreme Weather Events

Extreme weather events are somewhat ambiguously defined in the IPCC AR4:[11] *"An event that is rare at a particular place and time of year"*; one consequence of this is that the term is used somewhat diversely through the AR4 (Glossary). A key word in the IPCC definition is "rare," which in turn is defined as an event lying outside the 10th and 90th percentiles; it might be queried, however, whether an event that occurs on average once every five days at any location might be termed "rare."

Recognizing this, a Working Group at the NATO Advanced Research Workshop for Weather/Climate Risk Management for the Energy Sector suggested an alternative definition of extreme weather: "*an event on any time scale that contributes to stresses beyond the operating parameters of a sector*" (Troccoli, 2010a). This definition formally accepts that severe events cannot be defined in hydro-meteorological/climate terms alone, and therefore, as implied in the IPCC definition, they cannot be characterized uniquely using climate models, as location and economic activities at that location also play roles.

Hence the precise details, and in particular those specific to individual locations, of changes to climate that will stress aspects of energy sector operations remain unclear despite the oft-quoted IPCC expectation of increased frequencies of extreme events. Consequently, the energy sector at the present time may only take changes in weather producing stresses at a location into account in a risk management sense, taking full consideration of all possible scenarios at that location. The life cycle of each particular project should also be considered in this context, with, according to the IPCC, the more severe changes expected later.

Specifically for the impact of hurricanes, there have been ongoing debates in recent years in the scientific community, with some authors showing that there is an increase in destructiveness of hurricanes in the observed record (Emmanuel 2005; Webster et al., 2005). However, Pielke et al. (2008) argue that the normalized damage associated with U.S. mainland hurricane landfalls between 1900 and 2005 highlights the tremendous importance of societal factors in shaping trends in damage related to hurricanes (as people continue to flock to the nation's coasts and bring with them ever more personal wealth, losses will continue to increase).

As for future trends, Pielke et al. (2005) claim that links between global warming and hurricane impacts are premature for three reasons. First, no connection has been established between greenhouse gas emissions and the observed behavior of hurricanes. Second, the peer-reviewed literature reflects that a scientific consensus exists that any future changes in hurricane intensities will likely be small in the context of observed variability, while the scientific problem of tropical cyclogenesis is so far from being solved that little can be said about possible changes in frequency. And third, under the assumptions of the IPCC, expected future damages to society of projected changes in the behavior of hurricanes are dwarfed by the influence of its own projections of growing wealth and population. A more recent study shows that global warming should reduce the global frequency of hurricanes, though their intensity may increase in some locations (Emmanuel et al., 2008).

Summary Tables

Climate trends and projections of relevance to the energy sector have been discussed in the preceding sections and are summarized in Table 2.3.

Table 2.4 summarizes significant observed and projected changes in intra- and interannual variability of climate indicators of potential significance for the energy sector for the six World Bank geographic regions (Chapter 2, "Climatic Impacts on Energy Services" and" Recent Observed Climate Change"). Note that although the identified "hotspots" are relevant to the energy sector, it is not straightforward to assess their actual impact.

Table 2.3. Potential Impacts and Vulnerabilities of Energy Systems to Changes in Meteorological Variables

	Effects of changes in meteorological variables						
		Increased frequency and/or strength of extreme weather events					
Impacts on	**Temperature increase (average and min/max)**	**Storms/cyclones**	**Droughts**	**Floods**	**Changes in precipitation**	**Glacier melting**	**Changes in cloud cover**
Energy resources and generation							
Thermal power—fuel availability and generation	No impact on fuel availability Decrease of power plant efficiency due to higher temperature of cooling water	Decreased fuel availability if storms affect offshore oil platforms and open coal mines Decrease in generation if equipment is destroyed	Decrease in fuel availability and energy generation due to lack of water for cooling and other operations	Decrease in availability if floods affect mines Decrease in generation if power plants are flooded	The quality of coal is impacted by its moisture content	Increase in medium-term energy generation and decrease in the long-term	None
Hydropower	Increased reservoir evaporation and losses through vegetation reduces effective generating capacity	See Floods	Reductions in effective generating capacity due to reduced runoff and increased surface water evaporation	Forces storage conservation and/or spills that reduce effective generating capacity Physical damage	Changes in runoff effect generating capacity, through reduced storage and head	More rapid melting results in loss of potential generating capacity for existing reservoirs due to unplanned spills	None
Biomass	Effects Net Primary Production (NPP) of feedstocks Could increase or reduce NPP of existing feedstock supply Affects area needed to grow feedstocks and costs	Reduced feedstock supply in short run due to storm damage and increases area needed to grow feedstocks and costs	Reduces NPP of feedstock and increases area needed to grow feedstocks and costs	Reduces NPP of feedstock in affected areas and increases area needed to grow feedstocks and costs	Affects NPP of feedstocks. Could increase or reduce NPP and affects area needed to grow feedstocks and costs	If under irrigation: short-to medium term increase, long-term decrease	Reduction in NPP of feedstocks due to reduction in solar radiation
Wind	Power output decreases due to the decreased air density	Reduction in effective generating capacity due to forced shutdowns above max designed wind speed	None	Loss of effective generating capacity due to physical damage	Effects on soil stability and drainage affect stability of towers	None	None
Solar	Efficiency decreases	Physical damage from high wind and hail (Appendix E) reduces generating capacity	Likely to increase potential generating capacity of existing units	Local impacts on distributed systems due to local flood damage	See increased cloud cover	none	Reduced solar radiation reduces generating capacity

(continued)

Table 2.3 (continued)

Impacts on	Effects of changes in meteorological variables						
		Increased frequency and/or strength of extreme weather events					
	Temperature increase (average and min/max)	Storms/cyclones	Droughts	Floods	Changes in precipitation	Glacier melting	Changes in cloud cover
Energy transmission and distribution							
Energy transmission and distribution	Changes in capacity utilization due to temperature	Reductions in system reliability due to physical damages	Reductions in system reliability due to forest fire damages	Reductions in system reliability due to physical damages	See Floods	None	None
Energy use and demand							
Energy use and demand	Increase due to higher cooling needs. Decrease due to less need for space heating	Power outages to end users: decreased system reliability	See temperature increase: impacts on peak demands	Power outages to end users	See Floods	None	Reduction in solar radiation will affect some end uses, indirectly

Source: Generated by authors.

Table 2.4. Summary of "Hotspots"

	Africa	East Asia & Pacific	Europe & Central Asia	Latin America & Caribbean	Middle East & North Africa	South Asia
2-meter T	Sizeable projected changes in variability	Large errors in observed seasonal mean	Large observed variability; sizeable projected changes in variability	Large errors in observed seasonal mean; sizeable projected changes in variability		Large errors in observed seasonal mean
10-meter wind				Large observed variability over ocean	Large observed variability over NW Africa	
Solar radiation	Large errors in observed annual mean; sizeable projected changes in high-end extremes			Large errors in observed annual mean	Sizeable projected changes in high-end extremes	Large errors in observed annual mean; sizeable projected changes in high-end extremes
Sea level	Large observed changes					Large observed changes
Permafrost			Risk of degradation and reduction			
Sea ice	Reported acceleration of melting of Greenland and Antarctic ice sheets					

Source: Generated by authors.
Note: Hotspots were identified in Chapter 2, "Climatic Impacts on Energy Services" and "Recent Observed Climate Change", and hence are not comprehensive across all variables/statistics combinations. "Observed" refers to either direct observations or to outputs from re-analyses.

Notes

1. Although extremes in meteorological variables may be related to extreme events of significance to the energy sector, the two do not necessarily coincide (see Chapter 3, "Energy Transmission, Distribution, and Transfer," for a more detailed discussion on this difference).
2. According to IPCC AR4, re-analyses are atmospheric and oceanic analyses of temperature, wind, current, and other meteorological and oceanographic quantities, created by processing past meteorological and oceanographic data using fixed state-of-the-art weather forecasting models and data assimilation techniques. Using fixed data assimilation avoids effects from the changing analysis system that occurs in operational analyses. Although continuity is improved, global re-analyses still suffer from changing coverage and biases in the observing systems.
3. Climate models do not provide an adequate local representation of the current climate. After verification, global circulation models (GCMs) are valuable tools to assess long-term changes in large-scale climate features.
4. Only a selection of plots is presented here: a much wider "catalogue" is available (Appendix B).
5. The DESERTEC Foundation has evolved from a network of politicians, academics, and economists from Europe, the Middle East, and North Africa and the German Chapter of the Club of Rome, which jointly developed the DESERTEC Concept. The objective is to convert power production to renewable sources, in particular, harnessing the high energy potential of the world's desert regions. DESERTEC is a holistic concept that, besides energy security and climate protection, addresses the subjects of drinking water supply, socioeconomic development, international cooperation, and security policy. For more info, see: http://www.desertec.org/.
6. The ENSO phenomenon refers to changes in sea surface temperature (SST) in the eastern equatorial Pacific Ocean and can be categorized into three phases: El Niño (warm SST anomalies), La Niña (Cool SST anomalies), or neutral.
7. Some 25 climate models form this dataset, but they are not all completely independent of each other (for example, a model may be present with two similar versions).
8. A key challenge is accessing the cooling water needed for this type of solar power plant since it requires about 3,000 L/MWh (similar to a nuclear reactor). Dry cooling (with air) or hybrid dry/wet cooling can be used when water resources are limited: the former is an effective alternative used on the so-called integrated solar combined-cycle plants under construction in North Africa but is more costly and reduces efficiency. Energy demand could increase as a result of increased radiation (and heat).
9. "The Community Climate System Model (CCSM) is a coupled Global Climate Model developed by the University Corporation for Atmospheric Research (UCAR) with funding from the National Science Foundation, Department of Energy, and NASA. The coupled components include an atmospheric model (Community Atmosphere Model), a land-surface model (Community Land Model), an ocean model (Parallel Ocean Program), and a sea ice model (Community Sea Ice Model). CCSM is maintained by the National Center for Atmospheric Research" (http://en.wikipedia.org/wiki/Community_Climate_System_Model).
10. The Coupled Model Intercomparison Project (CMIP) began in 1995 under the auspices of the Working Group on Coupled Modeling (WGCM). The purpose of CMIP is to provide climate scientists with a database of coupled GCM simulations (with 30 coupled GCMs) under standardized boundary conditions. CMIP investigators use the model output to identify aspects of the simulations in which "consensus" in model predictions or common problematic features exist. (http://www-pcmdi.llnl.gov/projects/cmip/overview_ms/ms_text.php; http://en.wikipedia.org/wiki/Coupled_model_intercomparison_project).
11. An event that is rare at a particular place and time of year. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th *percentile* of the observed probability density function. By definition, the characteristics of what is called *extreme weather* may vary from place to place in an absolute sense. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (for example, drought or heavy rainfall over a season).

CHAPTER 3

Climate Impacts on Energy

Climate change will increasingly affect the energy sector. Although impacts on energy supply and demand are the most intuitive, climate change can also have direct effects on energy endowment, infrastructure, and transportation and indirect effects through other economic sectors.

While projected climate change is not commonly factored into conventional energy planning and operations, the role of energy as a driver of climate change is far more studied. Renewable energy plays a key role in future low-carbon-emission plans aimed at limiting global warming. However, its dependence on climate conditions makes it also susceptible to climate change. Although the first part of this "paradox" has been thoroughly studied (IPCC, 2007c), the international scientific community has recently started to investigate the impacts that global climate change may have on energy, in general, and renewable energy, specifically.[1] The formal knowledge base is still at an early stage of development (Willbanks et al., 2007).

This chapter discusses what is known about how energy systems can be affected by changing climate. Distinctions are made between energy endowment and supply. Energy endowment concerns the amount of primary energy available. Fossil fuels endowments refer to the energy stock and how climate change may affect access to these resources. Renewable energy endowments, on the other hand, refer to a flux of energy that is closely related to climate parameters. Energy supply, as discussed in this chapter, focuses on the technologies that convert primary energy into a form that can be used by consumers.

Impacts on Resource Endowment

Hydropower Resources

Hydropower generation depends directly on the availability of water resources, and therefore on the hydrological cycle that plays a major role in mountainous areas and valleys with significant slopes and stream flows. The usual methodological approach to assess climate impacts on hydropower resource endowments consists of translating long-term climate variables into runoff. Various hydrological models evaluate climate impacts on runoff using precipitation and temperature scenarios from GCMs. GCMs project, under various scenarios, that temperature anomalies in mountainous areas are likely to exceed those in surrounding lowlands (Bradley et al., 2006). Temperature anomalies under these conditions have the potential to affect runoff. Milly et al. (2005), using an ensemble of GCM outputs, identified major impacts on net runoffs due to changes in soil temperature, relative humidity, and runoff, even when precipitation is unchanged.

In the Andes cordillera in South America, high temperature anomalies are causing the accelerated retreat of tropical glaciers, the drying of unique neo-tropical alpine wetland ecosystems locally known as *páramos* or *bofedales*, and increased weather variability and weather extremes that affect ecosystem integrity and water regulation. In turn, these impacts may affect the economics of regional water and power supplies.

Such changes in hydrology will directly affect the output of existing and future hydro-electric facilities. Studies of hydro-electric power generation conducted in the Zambezi basin, taken in conjunction with projections of future runoff, indicate declining power production due to a significant reduction of river flows (Harrison and Whittington, 2002; Riebsame et al., 1995; Salewicz, 1995). A reduction in hydropower potential is also anticipated in areas where river flows are expected to decline, such as in the Rio Lempa basin and the Simú-Caribbean basin of Central America (Maurer et al., 2008; Noreña et al., 2009).

Climate change will impact water regulation and the ability to buffer the hydrologic response to seasonal variations in rainfall. This is a direct consequence of the expected intensification of the water cycle discussed in Chapter 2. An analysis made of annual stream flows in some rivers in South America under scenario A1B (Nakaegawa and Vergara, 2010; Vergara and Scholtz, 2011) found reductions in the stability of stream flows (higher high flows and lower low flows) and consequent impacts on firm capacities of dependent hydropower facilities. An analysis of the central range of the Andes,[2] in the vicinity of glaciated basins and Paramo biomes (Ruiz et al., 2010), found significant changes in runoff that would affect the functioning of water reservoirs used for power generation.

The extent to which this information can be used to estimate *actual* generation capacity, however, depends on the amount of information available. In a general way, the gross hydropower potential[3] can act as an indicative measure of possible trends related to climate change. However, this measure does not allow conclusions to be drawn on the actual consequences of climate change in the affected basins. For example, a loss of water regulation would require the expansion of multi-annual storage capacity that could absorb the variations in runoff and still keep the firm capacity of the reservoirs.

Further analysis of the impacts of projected climate change on new hydropower facilities can be difficult due to the lack of data about the technical parameters of new plants. This makes gross hydropower potential an interesting measure in some developing countries where data availability is an issue (for example, identified hotspots in Chapter 2). Assessing climate impacts on future hydropower capacity demands information that is imbued with uncertainty, especially at the large scale (in terms of remaining potential as opposed to site-specific information).

A second-order climate change impact on the endowment of water resources is associated with global warming effects on the competition for water resources among economic sectors, such as agriculture and water supply recreations. Climate change will exert its impact on other water users, which might contribute to new demands for water allocations, altering the potential use of the available hydropower endowment.

Multi-annual events, such as ENSO, may also have a negative impact on the ability to generate hydropower in otherwise well-regulated basins. Though a link between ENSO occurrences and climate change has not been conclusively demonstrated, the likelihood of warmer-than-usual sea surface temperatures both in the Pacific and in the North Atlantic could be inferred to be associated with climate change.

Wind Energy

The availability and reliability of wind energy[4] depends on current and future climate conditions due to the relationship between the energy density of wind, the global energy balance, and the atmospheric motion that results from it (Hubbert, 1971). Wind speeds (and their variability) define not only the economic feasibility of exploiting wind resources but also the reliability of electricity production once the capacity is installed.

Shifts in the geographical distribution and the variability of wind fields are the main mechanisms by which global climate change impacts wind energy endowments (Pryor and Barthelmie, 2010). For example, expected higher temperatures and low humidity in southeastern Europe are expected to be accompanied by shifts in the northern extent of wind fields in the Mediterranean that affect the endowment of wind energy (Murphy, 2008). And soil instability in permafrost areas affected by warming may compromise the construction of wind farms that involve the installation of large towers that are subjected to forces from the rotating turbine (Murphy, 2008).

Wind speed also varies significantly at different elevations. Though wind speed projections are not necessarily produced at the hub height of a wind turbine (above 50 m), there are methods to extrapolate wind speeds to different heights. Nevertheless, some climate variables can impact the vertical wind profile. For example, using the common logarithmic extrapolation, the roughness of the terrain is a key parameter affecting wind speed profiles (Dutra and Szklo, 2008). Terrain roughness can also vary with the type of vegetation cover, and thus climate impacts on vegetation cover (Nobre et al., 2007) can affect the assessment of wind power generation potential (for example, see Lucena et al., 2010a).

Liquid Biofuels

Liquid biofuels can be vulnerable to the effects of weather modifications on crops used as raw materials to produce ethanol and biodiesel. Climate change can affect regional temperature and rainfall patterns, the frequency of precipitation and extreme weather events (for example, droughts and frosts), as well as the level of carbon dioxide (CO_2), all of which have impacts on crops. Pinto and Assad (2008) show that high CO_2 levels, up to a certain saturation limit,[5] increase the photosynthesis rate and hence increase crop productivity. However, this effect is offset by rising temperature.

- Other direct effects on agriculture include changes in agricultural distribution zones, the incidence of plant pests, and the availability of lands suitable for growing some crops, as described by Siqueira et al. (2001):
- Temperature increases can modify soil conditions and impact crop fertility and productivity levels. This may be offset by higher photosynthetic activity in some cases.
- Higher CO_2 levels can cause a positive impact on CO_2-sensitive crops by improving photosynthesis.
- Each plant has a temperature range suitable for its growth, and an alteration in regional temperature variations is expected to cause a modification in regional agricultural profiles.
- Rising temperatures can lead to a higher rate of evapo-transpiration in plants and reduce productivity or even make an area unsuitable for cultivation.

- Temperature increases can affect the metabolism of insects, accelerating their reproduction and increasing the incidence of pests.
- Extreme climate conditions, such as droughts, frosts, fires, and storms, can affect crops, crop patterns, productivity, and their vulnerability to pests.

Solar Energy

Solar energy resources have varied in recent times, with variations in solar activity that alter the solar input at a planetary level (Bard and Frank, 2006). These oscillations, however, bear no relation to climate change. Nevertheless, climate change can affect the solar energy resource by changing atmospheric water vapor content, cloudiness, and even cloud characteristics that affect atmospheric transmissivity (Cutforth and Judiesh, 2007). This can impact electricity generation from photovoltaic and concentrated solar power.

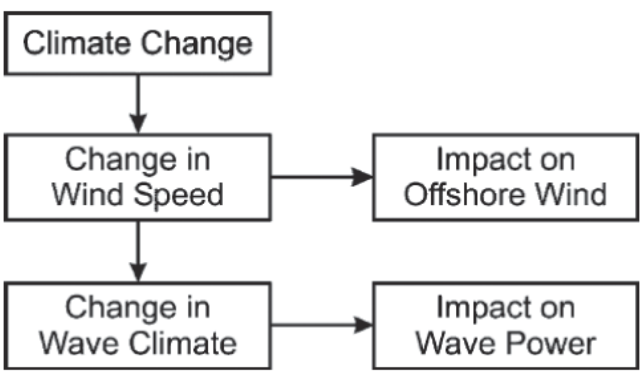
Wave and Tidal Energy

There are several ways in which the ocean can provide energy, with wave energy being the most commonly used ocean energy source worldwide, although it is still not developed nor disseminated to the same extent as other renewable energy resources.

Climate change impacts on wind energy have important direct impacts on wave formation (Figure 3.1). Wind climate effects and wave generation have a nonlinear relationship and show different long-term trends around the globe. For example, Harrison and Wallace (2005) showed that a 20 percent decrease in mean wind speed lowers available wave power levels by 67 percent, while an equivalent increase raises them by 133 percent under fixed conditions.

In some regions there have been positive impacts on wave energy and an increasing trend in wave height; for example, analyses of annual maximum significant wave heights based on data from 1955–1999 strongly indicate increasing wave heights and a rougher wave climate off the coast of mid-Norway (Vikebo et al., 2002). In other regions, wave heights and energy have declined; for example, wave modeling for the southern Californian coast showed a negative trend for wave height, and thus wave energy (Cayan et al., 2009).

Figure 3.1. Climate Change Impacts on Wave and Wind Energy



Source: Harrison and Wallace, 2005.

No references have been found on climate change effects on tidal energy. It is possible that sea level rise could alter tidal basins and affect the tidal range. Tidal currents may also change as a result of sea level rise; for example, inundation may cause an enlargement of the tidal channel and a resulting smaller tidal current speed, but, once again, this may not be relevant, and no scientific references have been found to support this.

Oil and Gas Resources

Oil and gas resources are not likely to be impacted by climate change because they result from a process that takes millions of years and are geologically trapped. On the other hand, climate change may not only force the shutting down of oil- and gas-producing areas (for example, those lying on melting permafrost in Alaska; Bull et al., 2007), but increase the feasibility of exploration in areas of the Arctic through the reduction in ice cover. Thus, while climate change may not impact these resources, oil and gas reserves and known or contingent resources could be affected by new climate conditions, since climate change may affect access to these resources. In Siberia, for instance, the actual exploration challenge is the time required to access, delineate, produce, and deliver oil under extreme environmental conditions, where temperatures in January range from −20°C to −35°C (Dienes, 2004). Warming may ease extreme environmental conditions, expanding the production frontier.

Impacts on Energy Supply

Energy transformation facilities can be affected by climate change in a variety of ways, as discussed in the following sections. It is worth noting that a major share of the current energy system (and even the energy facilities under construction or planned to be built in the next years) will likely remain operational under new climate conditions given the long life span of energy infrastructure. However an analysis of climate impacts on short-lifespan technologies inherently implies that the facilities would be replaced over time by similar technologies at the same location. Thus, for technologies where there remains room for technological advances or relocation, climate impacts can be overestimated. Spontaneous adaptation measures can also offset some impacts that were originally projected.

Hydropower Generation

The amount of electricity that can be generated from hydropower plants depends not only on the installed generation capacity, but also on the variation in water inflows to the plant's reservoirs. Natural climate variability already has a great influence on the planning and operation of hydropower systems. Most systems are designed taking into account historical records when determining the amount and variability of energy produced over daily or seasonal fluctuations. This assumes a stable climate. Changing climate conditions can affect the operation of existing hydropower systems and might even compromise the viability of new investments. In fact, global climate change can add a significant amount of uncertainty to the already uncertain design and operation of hydropower systems (Box 3.1).

A methodological approach that is commonly applied to assess climate impacts on hydropower generation uses climate change simulated river flows in an electric power model (for example, Hamlet et al., 2009; Lucena et al., 2009a) Some studies include an economic evaluation of investment returns or revenue maximization (for example, Har-

Box 3.1. Projected Changes in Hydropower Generation

Modeling by the Norwegian University of Science and Technology examined climate impacts on river flows and hydropower generation to 2050. Systems at highest risk had both a high dependence on hydropower generation for electricity and a declining trend in runoff. South Africa is quoted as one example with a potential reduction of 70 GWh per year in generation by 2050. Afghanistan, Tajikistan, Venezuela, and parts of Brazil face similar challenges.

Source: Hamududu and Killingtveit, 2010.

rison and Whittington, 2002; Vicuña et al., 2005).[6] The river flow series is simulated in hydrological models, which are in turn calibrated to current climate but forced with climate variables (normally from downscaled GCM data), such as precipitation and temperature for selected emission scenarios.

The modeling tools for analyzing climate impacts on a hydropower system ultimately depend on the complexity of the system, for which two factors can be highlighted (Lucena et al., 2009b). The first is how relevant hydropower generation is for the whole power system, in other words, whether hydroelectricity is complementary to (for example, the United States and Western Europe) or complemented by (for example, Brazil and Norway) other power sources. If hydroelectricity is complementary to other generating sources, average values for hydropower production generally provide a sufficient measure of climate impact. On the other hand, power systems fundamentally based in hydropower must be assessed in terms of a more conservative indicator, such as firm power,[7] to minimize the risk of power shortages.

The second factor relates to geographical dispersion and the level of integration through transmission capacity. Transmission may play an important role in coping with regional climate variations in interconnected hydropower systems that cover a vast area. In Brazil and Colombia, for example, electricity transmission networks help to optimize the power system's operation by compensating for regionally different seasonal variations (Lucena et al., 2010b; UPME 2009). In such a case, just as the operation of different plants along the same river should not be optimized individually, the rationality of a central dispatch center makes more sense.

The characteristics of individual plants can influence the vulnerability of hydropower systems to climate change. For example, river flow can be highly variable, especially across seasons, and small run-of-river plants offer little operational flexibility and are more vulnerable to climatic variations. Reservoir storage capacity can compensate for seasonal (or even annual) variations in water inflow, enabling matching of electricity generation to varying power demand. In some regions where snowmelt is part of the hydrological cycle, the ability to store water can help reduce potential seasonal shifts caused by earlier melting or could even partially compensate for glacier retreat. Snowpack acts as a natural reservoir during winter but climate change could increase river flow in spring and reduce it in the summer. If the built reservoirs are not designed to manage earlier increased flows, energy can be wasted through spillovers (Vicuña et al., 2005).

Wind Power Production

Wind energy cannot be stored[8] nor have its output regularized, and hence the natural hourly, daily, or seasonal variability of wind speed has a significant impact on the energy produced from wind turbines. Natural variations in wind speeds may not match power demand fluctuations.

The energy contained in wind is proportional to the cube of the wind speed, which means that alterations in the latter can have significant impacts on the former (Pryor and Barthelmie, 2010). Any analysis of climate impacts on wind energy supplies should therefore include the frequency distribution of wind speeds as well as the average value. Alterations in the wind speed frequency distribution can affect the optimal match between power availability from natural resources and the power curve of wind turbines. Downscaled climate projections have serious limitations when reproducing wind speeds, frequency distribution, and directional wind changes (Pryor and Barthelmie, 2010). Still, numerous studies discuss the impacts of climate change on wind power[9] (for example, Breslow and Sailor, 2002; Lucena et al., 2010a; Pryor et al., 2005a, 2005b; Sailor et al., 2000, 2008; Segal, 2001).

Although wind power production is likely to be potentially more vulnerable to the negative impacts of climate change than hydropower generation, wind power systems have smaller life spans, making them more adaptable in the longer term. The decision to build a hydropower dam entails not only high capital and environmental costs but also a stationary structure with a longer physical and economic life span.

In this context, climate impact studies on wind power systems should focus on the total exploitable wind resource, indicating the future availability of power generation and identifying/prioritizing areas for site-specific viability assessments.[10] In some cases complementarities have been found between wind regimes and precipitation cycles (Vergara et al., 2010).

Solar Energy

Solar energy generation can be affected by extreme weather events and increased air temperature that can modify the efficiency of photovoltaic (PV) cells and reduce PV electrical generation (Bull et al., 2007). A reduction in solar radiation can also reduce efficiency. For example, a 2 percent decrease in global solar radiation will decrease solar cell output by 6 percent overall (Bull et al., 2007; Fidje and Martinsen, 2006).

The efficiency of CSP generation can be impacted by climate change. CSP is a thermal generation process and its efficiency is altered by temperature change. In addition, CSP based on solar electric generation systems follows a Rankine cycle requiring increased water use and with lower generation efficiency (Chapter 3.2, "Thermal and Nuclear Power Plants").

Liquid Biofuels

Pinto and Assad (2008) assessed the impacts of declining crop productivity in Brazil on liquid biofuels supplies. In aggregate, the productivity of sugarcane crops could be positively affected by climate change. Southern areas of Brazil could become less vulnerable to frosting events and hence more adapted to sugarcane production. Existing areas with high productive potential would remain suitable for sugarcane crops but would increasingly require irrigation during dry periods. The authors also studied the impacts on soybeans and concluded that soybean productivity in the southern and northeastern regions of Brazil would decline by 40 percent due to longer periods of drought and reduced water availability.

Persson et al. (2009) modeled changes in the grain yield of maize used for ethanol production resulting from changing crop management practices associated with climate variability. Modeling took into account the ethanol net energy value[11] conditions for the southeastern region of the United States and climate behaviors associated with the ENSO phenomenon.[12] Modeling results showed that maize production used as feedstock in ethanol production is, in fact, affected by climate variability, since maize yield varies significantly with the ENSO phases.

Thermal and Nuclear Power Plants

Climate impacts on fossil-fuel-fired, nuclear, and biomass-fired power production are mainly related to generation cycle efficiency and water requirements for cooling (CCPS, 2007). The impacts derive from heating and cooling needs of both the Rankine and Brayton thermodynamic cycles, which vary according to average ambient conditions such as temperature, pressure, and humidity, as well as cooling system efficiency. The efficiency and reliability of energy supplies from coal, natural gas, nuclear, biomass, and geothermal[13] technologies can all be affected. Although these impacts tend to be relatively small, as observed by Bull et al. (2007), when an energy system is highly dependent on this type of generation, even a modest variation in ambient temperature may represent a significant drop in energy supply.

Coal-fired and nuclear power plants both operate under a Rankine cycle. Increased temperature raises the specific volume of air and energy consumption in the compressor and reduces the amount of net energy generation (Schaeffer et al., 2008).

Natural-gas-based generating units are also affected, as demonstrated in a study by Davcock et al. (2004) (of capacity and heat rate) under forecast ambient and actual unit equipment conditions. They concluded that a 33°C increase in ambient temperature (common in deserts on a daily basis) could cause an 8.4 percent reduction in the heat rate and a 24 percent reduction in the power output of a single-cycle gas turbine. Though 33°C represents a wide variation, turbine performance could still be impacted by smaller temperature swings (for example, a 5.5°C change). Collectively, a number of individually small impacts could add up to a significant loss in power generation in a specific region.

Arrieta and Lora (2005) conducted a parametric study of a combined-cycle power plant with a net electricity capacity of 600 MW and a supplementary firing system. They considered an ambient temperature range of 0^{o}C to 35^{o}C and different gas temperatures after supplementary firing (ranging from 675^{o}C to 525^{o}C). They concluded that temperature influenced the generating unit, varying its net power by up to 12.5 percent of installed capacity under the temperature range considered.

The significant amounts of water that are needed to cool thermal power facilities make them vulnerable to fluctuations in water supplies. Water availability is an issue at the regional scale, which means that some areas would experience a significant increase in water supply, while other regions would face the opposite (Bates et al., 2008). In the United States, for example, each kWh of electricity generated by a steam cycle process requires around 94.6 liters of water[14] (Bull et al., 2007). Feeley et al. (2008) evaluated the withdrawal and consumption[15] of water for different cooling systems[16] under a range of climate scenarios. The results show that water withdrawal may decline by 30 percent compared to a 2005 base year and water consumption may increase by almost 50 percent by 2030. That is, although less water would be required by the cooling system, losses, mainly caused by evaporation, would increase, reducing the volume of water returned to water bodies.

With climate change, coal-based generation will increasingly be linked with carbon capture and storage (CCS) technology that will increase the demand for water to cool amine-based wet scrubbing processes and for CO_2 compression. This could as much as double the amount of water used per kW of electricity delivered. By 2030 additional CCS technology could increase the water consumption in the United States's electric power sector by 80 percent (ca. 7500 megaliters per day) (Moore 2010; NETL, 2009). This means that a 550-MW power plant would need an additional 125 MW of capacity to replace the energy consumed at the site for CCS and power generation to be able to deliver 550 MW of electricity.[17]

Rising temperatures can also increase water temperatures and negatively affect a plant's cooling efficiency. This can in turn increase the demand for water. Heat waves and similar extreme conditions may place additional severe limitations on plant operations. This was exemplified during the heat wave of 2003 in Europe (Letard et al., 2004), when social and environmental considerations reduced the availability of cooling water, restricting—when most needed—the energy supply.

Changes in water availability will have impacts for new construction and the operation of existing plants that will increasingly compete with other water users (such as agriculture and public supply, especially in water-stressed areas; Bull et al. 2007; Feeley et al. 2008). New plants will have to be carefully analyzed when making decisions about their location to avoid water-stressed areas. Bull et al. (2007) illustrates this issue for power plant projects in Arizona and New York, where plans are being denied and re-evaluated.

The type of cooling technology used can reduce a plant's exposure to these changes. Koch and Vögele (2009) simulated water demand projections and the future availability of water for power plants in the river Elbe basin, in central Europe. Their results show that power plants with closed-circuit cooling systems are less vulnerable to changes in the temperature of water supplies than once-through systems, since an increase in ambient air temperature of a few degrees Celsius has no significant effect on water demand.[18]

Summer water demand for once-through systems, on the other hand, could rise by 30 percent.

Biomass-based thermal power generation can additionally be affected by changes in crop productivity and hence the availability of raw materials. However, in some regions the use of biomass residues (for example, sugarcane bagasse) for thermal generation can help promote diversity in the energy system, thus increasing resilience to climate change effects (Schaeffer et al., 2008).

Oil and Gas Production

Oil and gas production from offshore facilities, as well those located in low-lying coastal areas, can be disrupted by extreme events, such as more intense hurricanes, that can lead to production shutdowns for evacuation to avoid loss of life or environmental damage (API, 2008). Hurricanes in the Gulf of Mexico in 2004 and 2005 resulted in a large number of destroyed and damaged offshore oil and gas structures: more than 124 platforms were destroyed and over 660 structures were extensively damaged (Bull et al., 2007). An increase in the frequency, duration, and intensity of such extreme events can therefore have significant impacts on oil and gas production.

Production may also be affected by structural damages caused by other extreme events, such as flooding due to sea level rise and storm surges that may cause erosion and other damage (Cayan et al., 2009). At high latitudes (for example, near the Arctic), rising temperatures and permafrost melt can compromise the structural integrity of the energy transfer and production infrastructure built upon it (for example, in areas of Alaska's North Slope, change is already being observed—Bull et al., 2007; see also Chapter 3, "Energy Transmission, Distribution, and Transfer").

Oil refining is a large water consumer and is thus affected by lower water availability. Total water consumption in an average U.S. refinery is estimated at 65 to 90 gallons of water per barrel of crude oil (Energetics, 1998). Some refineries already face water resource competition issues without considering climate change (for example, REPLAN, the largest refinery in Brazil). Water demand in oil refineries can also rise as a result of higher temperatures and its use in cooling units (around 50 percent).

Energy Transmission, Distribution, and Transfer

Widely ranging weather and climate situations can impact the transmission and distribution of power, and the transfer of oil, gas, and other fuels. This is especially true in the case of transmission lines and pipelines that can extend thousands of kilometers and be exposed to wind gusts, storms, icing, storm-related landslides and rock falls, land movements, and siltation and erosion processes. Land-based transfers of energy (by road or rail, for example) are similarly exposed.

Extreme winds and ice loads, combined wind-on-ice loads, lightning strikes, conductor vibrations, and galloping, avalanches, landslides, and flooding, can cause power transmission and distribution lines to fail. In particular, excessive icing on overhead lines can cause power outages and millions of dollars of repair costs (Musilek et al., 2009). Distribution systems are also vulnerable to meteorologically induced factors such as falling trees (for example, due to high winds).

Oil and gas pipelines can be impacted by a range of weather and climate factors. For example, the Russian Gas Transmission System totals over 1 million kilometers that

Figure 3.2. Extreme Ice and Snow Loads on Pylons Near Münster, Germany, in Autumn 2005

Source: Picture by Picture Alliance/Franz-Peter Tschauner.

operate under different natural conditions. Collectively the system is exposed to mud flows, floods, landslips, permafrost thawing, and other extreme meteorological events as well as to geological hazards such as earthquakes, rock falls, karsts and suffusion phenomena, and subsidence of loess-type rock. Climate change increases the probability, recurrence, and distribution of natural disasters (heavy precipitation, high temperatures, strong winds, and floods) in Russia, which may be a factor in initiating unfavorable geodynamic processes (Vlasova and Rakitina, 2010).

Power transmission systems and pipelines may also be vulnerable to river and creek siltation and other erosion processes caused by changes in the hydrologic response of a water basin. Climate change is altering the geo-morphological equilibrium of river systems, with consequences for crossings and riparian infrastructure.

The transfer of energy by sea may face increasing challenges and opportunities. For instance, as Arctic sea ice melts at unprecedented rates, new shipping routes will open up. The world's ships are already sailing past western and northern Alaska. In autumn 2009, two container ships traveled north through the Bering Strait, escorted by Russian icebreakers.[19]

In addition to climate impacts on energy transfer, transmission, and distribution infrastructure, unexpected changes in energy demand may impose stresses on these systems. For example, excessive demand for air conditioning in hot weather may affect the efficiency of energy distribution.

Investment in new, expanded, and regionally integrated transmission lines—such as those planned under the DESERTEC concept, for the wind energy grid in Northern Europe,[20] for renewable energy in the western[21] and eastern[22] regions of the United States, under the African Renewable Energy Technology Platform (AFRETEP),[23] or even the embryonic Desertec Australia[24]—might help to mitigate climate impacts.

Energy Demand

Final energy use can be affected by rising temperatures and changes in rainfall patterns. The most direct and obvious effect relates to higher temperatures. This can lower demand for heating and increase demand for cooling (or air conditioning). The performance of motors and engines can also vary with changes in climate parameters. Finally, climate change can affect water (and electricity) demand in industries (for water quenching or refrigeration) and the water (and electricity) demand in agriculture for irrigation purposes.

The analysis of how climate variables affect energy demand is an important theme for energy planning and operations. The main studies in this area evaluate effects on energy use for heating and cooling due to projected temperature change. In general, climate projections are used as exogenous parameters in energy end-use or econometric models.

The first studies on this subject date from the late 1980s. Bhartendu and Cohen (1987) calculated the energy demand for heating (winter) and cooling (summer) in Ontario, Canada, using regression analysis for scenarios that doubled the atmospheric concentrations of CO_2. Baxter and Calandri (1992) estimated changes in consumption and peak load in California in the United States for two scenarios of global warming in 2010 using a energy end-use model for heating, cooling, and pumping/transport of water (see Chapter 3: Regional Demand).

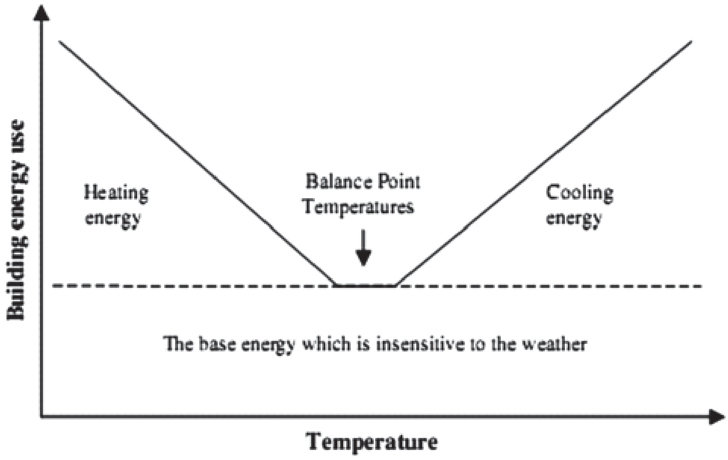
Heating and Cooling in Buildings

Worldwide, households consume about a third of all end-use energy. Globally, energy use in the household sector increased between 1990 and 2005 by 19 percent to reach 82 EJ.[25] Households are the only major end-use sector where the increase in energy consumption since 1990 has been greater in OECD countries (+22 percent) than in non-OECD countries (+18 percent) (IEA, 2008). In countries with a temperate climate, more than half of this energy is typically used for heating. Although space cooling is currently a much less important energy use, it is growing rapidly both in high-income countries and in emerging economies such as India and China (Isaac and Vuuren, 2009).

In a business-as-usual scenario, global energy demand for heating is projected to increase until 2030 and then stabilize. In contrast, energy demand for air conditioning is projected to increase rapidly over the period to 2100, mostly driven by income growth (Isaac and Vuuren, 2009).

Various empirical studies have found that total energy demand depends on outdoor temperature in a U-shaped fashion: low temperatures correspond to relatively high energy demand (higher energy demand for heating), intermediate temperatures correspond to lower energy demand, and high temperatures correspond to higher energy demand again (higher energy demand for cooling) (Guan, 2009; Hekkenberg et al., 2009; Thatcher, 2007).

Figure 3.3. Relationship between Building Energy Use and the Outdoor Temperature



Source: Guan, 2009.

This U-shaped pattern suggests that climate change may have ambiguous consequences for future energy demand, with the overall balance for energy demand varying regionally and seasonally (Figure 3.3).

This kind of analysis is usually studied using the concept of heating degree days and cooling degree days. Heating degree days is the sum of negative deviations of the actual temperature from the base temperature over a given period of time. The base temperature is defined as the temperature level where there is no need for either heating or cooling.[26] Cooling degree days is the sum of positive deviations between the actual temperature and the base temperature.

This energy impact is not restricted to modifications in the accumulated temperature deviations from a base value (the degree days). Additional demand for energy could arise from energy inputs for heating and cooling equipment. This additional energy demanded could be expressed by the coefficient of performance (COP) of the apparatus, with represents the relation between the useful energy extracted and the energy consumed (usually in electric power devices, such as compressors). According to the fundamental heat equation,[27] the amount of useful energy is directly proportional to the change in temperature. Therefore, assuming that the coefficient of performance of cooling and heating equipment doesn't change, an increase in the temperature variation increases the number of hours the apparatus is working, in turn raising energy consumption.

Global Demand

At the global level there are few studies that model heating and cooling demand in relation to the present climate and future climate change.[28] Isaac and Vuuren (2009) attempted to estimate climate impacts on global energy demand through end use (heating and cooling) by using simplified relationships based on the activity, structure, and intensity effects. In this study, heating energy demand decreased by 34 percent worldwide by 2100 as a result of climate change, and air-conditioning energy demand rose by 72 percent.

Regional Demand

Numerous studies look at climate impacts on regional energy demand, as summarized in Table 3.1. The general conclusion is that the climate impacts will vary across regions. Tropical areas will experience increased energy consumption for cooling and temperate regions will experience reduced energy demand for heating. From a global perspective, increased cooling tends to be higher, and new demand for cooling in countries with a tropical climate could induce energy supply bottlenecks.

Finally, it is worth stressing that changes in temperature will likely affect the use of air conditioning not only in residences but also in light vehicles, altering fuel consump-

Table 3.1. Studies Related to Climate Change Impacts on Regional Energy Demand

Study	Region/sector analyzed	Methodology	Detail	Change in energy consumption (%)	Temperature change (˚C) & date for change
Wang et al. (2010)	Australia (five cities), residential sector	Software developed by coupling a frequency response building thermal model and a multi-zone ventilation model	Total heating/ cooling energy requirement of newly constructed 5-star houses	-19 to +61%	Scenario 550 ppm (2050)
				-27 to +112%	Scenario 550 ppm (2100)
				-23 to +81%	Scenario A1B (2050)
				-37 to +193%	Scenario A1B (2100)
				-26 to +101%	Scenario A1FI (2050)
				-48 to +350%	Scenario A1FI (2100)
Dolinar et al. (2010)	Slovenia (two cities)	Simulation of the indoor conditions and the energy use for heating and cooling	Two types of buildings: standard and low energy	Heating: -14 to -32% Cooling: -3 to +418%	Scenarios in next 50 years: temperature rise (+1°C and +3°C) and solar radiation increase (+3% and +6%)
Pilli-Sihvola et al. (2010)	Five countries in Europe	Econometric multivariate regression model (degree days and others)	Focus on electricity demand	During summer, electricity demand will increase 2.5% to 4% by 2050 compared with 2007	A2, A1B, and B1 IPCC emission scenarios—2050 horizon
Schaeffer et al. (2008)	Brazil, residential and commercial sectors	Degree-days method and coefficient of performance effect	Focus on electricity demand (air conditioning)	Increase in electricity consumption in the country of 8% by 2030 (worst case)	A2 and B2 IPCC emission scenarios
Mirasgedis et al. (2007)	Greece	Econometric multivariate regression model (degree days and others)	Focus on electricity demand	Increase of the annual electricity demand of 3.6% to 5.5%	A2 and B2 IPCC emission scenarios, 2100 horizon
Thatcher (2007)	Australia (four cities), residential sector	Linear regression model adapted to include intraday variability	Focus on electricity demand	Change in peak regional demand between -2.1% and +4.6%	1°C increase in the average temperature
Hadley et al. (2006)	United States	Degree-days method: heating degree days (HDD) and cooling degree days (CDD)	Primary energy, residential and commercial combined	Heating -6%, cooling +10%, +2% primary energy	+1.2°C (2025)
				Heating -11%, cooling +22%, -1.5% primary energy	+3.4°C (2025)

(continued)

Table 3.1 (continued)

Study	Region/sector analyzed	Methodology	Detail	Change in energy consumption (%)	Temperature change (˚C) & date for change
Ruth and Lin (2006)	U.S. State of Maryland, residential and commercial sectors	Econometric multivariate regression model (degree days and others)	For each sector the demand for electricity, natural gas, and heating oil is separately estimated	Future energy prices and regional population changes may have larger impacts on future energy use than future climate	Mid-range (25 years) of temperature changes (+31F in spring and +41F in summer, fall, and winter)
Christenson et al. (2006)	Switzerland (four cities)	Degree-days method: heating degree days (HDD) and cooling degree days (CDD)	Focus on HDD and CDD (not energy focus)	HDD: -13 to -87% CDD: up to + 20 times (2085 scenario)	A2 and B2 IPCC emission scenarios
Mansur et al. (2005, *apud* Scott and Huang [2007])	United States, residential sector	(not available)	Focus on residential heating	-2.8% for electricity-only customers; -2% for gas customers; -5.7% for fuel oil customers	+1° C January temperatures (2050)
Amato et al. (2005)	U.S. State of Massachusetts, residential and commercial sectors	Econometric multivariate regression model (degree days and others)	For each sector the demand for electricity, natural gas, and heating oil is separately estimated	2.1% and 1.2% increase in per capita residential and commercial electricity consumption (2020)	GGE scenario assumed a 1% annual increase in equivalent CO_2
Baxter and Calandri (1992)	U.S. State of California,	End-use energy models (heating and cooling of buildings and pumping and transport of water for farms and cities)	Annual electricity use and peak demand	Electricity will increase by about 7,500 GWh (2.6%) and 2,400 MW (3.7%) by 2010	A 1.9°C increase
Bhartendu and Cohen (1987)	Ontario, residential sector	Econometric multivariate regression model (degree days and others)	The demand for electricity, natural gas, and heating oil is separately estimated	Heating energy: - 31 to -45%; Cooling energy: + 6 to +7% (Compared to 1976 -1983)	Doubling of atmospheric CO_2 concentrations (2 × CO_2) assumed to occur during 20252065

Source: Generated by authors.

tion. According to Parker (2005) and Scott and Huang (2007), the use of air conditioning reduces the efficiency of vehicles by about 12 percent at highway speeds. Roujol and Joumard (2009) found a positive relationship between temperature and fuel consumption in vehicles (around 0.01 and 0.03 liters/°C hour).

Demand from Industry and Agriculture

Industrial energy demand is particularly sensitive to climate change (Scott and Huang, 2007). The temperature differences that are bridged in industrial processes through cooling systems are often much larger than outdoor temperature fluctuations. Many continuous processes operate at relatively stable surrounding temperatures and thus have a relatively stable demand. However, continuous cooling processes related to food processing and storage, for example, have relatively small temperature differences to bridge and are possibly more sensitive to outdoor temperature variations (especially since these cooling processes often exchange heat with the outdoor air). Therefore some of the base electricity demand may be expected to be temperature dependent (Hekkenberg et al., 2009). However, little information exists on the impact of climate change on energy use in industry.

In the agricultural sector a warmer climate might lead to a rising demand for water and irrigation, and therefore increase the use of energy (either natural gas or electricity) for pumping. The Australian government's Water for the Future Initiative supports AU$ 5.8 billion in modernized irrigation infrastructure to secure water supplies for agriculture but will consume more energy through drip irrigation and pressurized pipelines (Australian Government, 2010). The demand for cooling of livestock and poultry facilities would similarly be expected to increase in a warmer climate, and heating needs in cattle barns and chicken houses would likely fall (Scott and Huang, 2007). However, no quantitative estimates of these effects were found.

Impacts on Design and Operations

Design Considerations

Global climate changes will impose a set of new conditions that some existing energy infrastructure may not be designed to withstand. This section discusses possible impacts on energy infrastructure due to the increased frequency and intensity of extreme weather events[29] triggered by climate change.

Coastal infrastructure is vulnerable to coastal erosion and siltation. Coastal erosion and siltation are complex processes affected by sea climate, wind direction, sediment availability, and the presence of geologic determinants. Climate change is likely to alter the geomorphodynamic equilibrium in coastal zones prone to sediment movements. Sediments availability is a function of the solid discharge of nearby rivers, sediment production from beach erosion and weatherization, and incoming sediments from sea currents and sea-related coastal processes. Sediment transport, the underlying phenomena, is very sensitive to changes in the flow regime.[30]

Low-lying coastal facilities are additionally vulnerable to sea level rise and extreme events (such as intense hurricanes). Sea level rise may be accompanied by more severe storm surges (which may flood a larger area) and coastal erosion (Cayan et al., 2009). In many countries, infrastructure is located in low-lying coastal areas. In the United States, for example, one-third of oil refining and processing facilities are located in key coastal areas (Karl et al., 2009).

Offshore oil and gas infrastructure, such as fixed platforms and pipelines, are particularly vulnerable to extreme events such as hurricanes that can structurally damage jackets and risers (Energo, 2006). The increase in wind, rain, storm surges (Karl et al., 2009), and wave height (Energo, 2006) caused by hurricanes may cause the critical failure of offshore pipelines, and platforms may suffer deformation generally as a result of wave inundation and disconnection from their moorings (Neumann and Price, 2009). This can compromise oil and gas production or even lead to shutdowns. In 2005 it took 12 months to restore production to pre-storm levels in the Gulf of Mexico (API, 2008). The damage inflicted by Hurricane Katrina on energy infrastructure in the Gulf of Mexico in August

2005 is another example. Oil production, imports, and refining were interrupted, having a major effect on fuel prices. According to the Insurance Information Institute, between US$2 and US$3 billion of insured damages occurred at offshore energy facilities (Insurance Information Institute, 2006). Climate change projections indicate a high likelihood that the number of intense hurricanes (categories 4 and 5) will increase over the next decades.

Other extreme events can pose a threat too. For example, two colder-than-normal winters in Russia in 2005–2006 and 2009–2010 led to severe disruptions in natural gas supply to Europe. Electric power transformers failed in the 2006 summer heat wave, impacting several areas of the United States (Karl et al., 2009). In general, higher variability will affect operation and maintenance costs.

Operational Considerations

Climate change can lead to unscheduled maintenance or increase the likelihood of situations in which plants may not be able to operate. Such events are commonly, but not necessarily, associated with extreme weather events.

In wind power generation, climate change may reduce the frequency of icing on turbine blades but can also affect turbine performance and durability (Pryor and Barthelmie, 2010). Icing is a major cause of wind turbine downtime at high altitudes and arctic latitudes.[31] Extreme wind speeds may exceed the maximum operating conditions for an installed turbine design and cause production[32] to shut down and a reduction in the capacity factor of wind power generation. How extreme wind speeds and gusts will alter operations in specific sites is a stringent challenge for climate science (Pryor and Barthelmie, 2010).

In the case of hydropower plants, reservoir capacity may limit the ability to manage an increased inflow of water, which can not only cause energy waste through spillovers but also compromise the safety of the dam. As an example of the first, Vicuña et al. (2005) found that climate change alters the seasonality of flow due to earlier snowmelt and a greater share of precipitation in the form of rain in California. They show that the reservoirs analyzed were not dimensioned to accommodate this earlier higher flow, leading to greater spillage and less overall energy generation. In the second case, the sub-dimensioning of spillways may even compromise the actual structure of the dam.

Transmission of energy can be a bottleneck in the event of regionally diverse impacts over integrated energy regions. For example, Lucena et al. (2010a) found that impacts on hydropower production in Brazil may be much more severe in the northeastern region of the country. Given the integration of the Brazilian power system through transmission, potential negative impacts could be offset by energy transfer from southern regions. However, transmission capacity needs to be properly dimensioned for the extra load in such an extreme case.

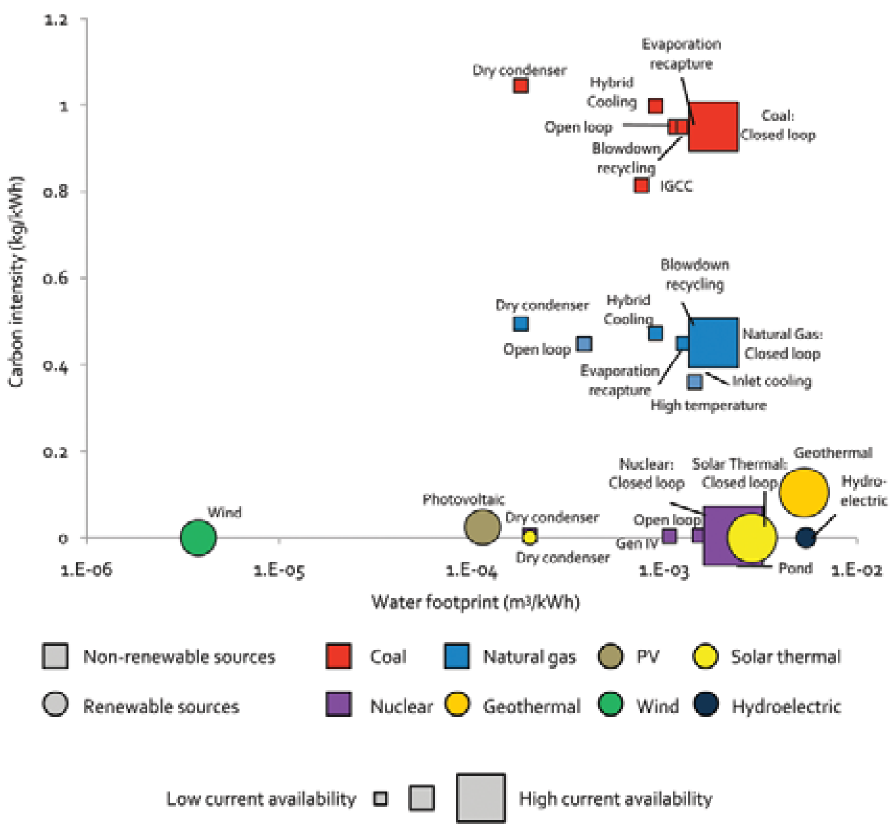
Cross-sector Considerations

Impacts of climate change on energy systems may have indirect effects on other economic/natural systems. Likewise, impacts on economic and natural systems can affect the supply and demand for energy. One of the greatest challenges when assessing impacts of climate change is to do so in an integrated way so as to fully take into account the many complex inter-relationships not only within the energy sector, but also in other sectors (Lucena et al., 2009b). Competition for water resources (for example, for electricity generation) is a key cross-sector impact that has been identified in preceding sections.

Most climate change impact assessments focus on water availability. A few studies also include comparisons with projected demand to test the vulnerability of water supply (for example, Arnell, 1999; Dvorak et al., 1997; Joyce et al., 2005; Lettenmaier et al.; 1999; Wilby et al., 2006). In general, however, there is limited attention on the demand side. Changes in land use, higher water demand for crop irrigation, and population shifts caused by climate change are some of the issues that can affect the demand for water resources (Frederick and Major, 1997). Multiple uses of water resources (such as human and animal consumption, irrigation, ecosystem maintenance, and flood control) add significant complexity to energy modeling. Similarly, it adds a large amount of uncertainty to climate impact assessments on energy systems.

The 2009 Market Report by Lux Research, "Global Energy: Unshackling Carbon From Water," examined the carbon and water intensity of power production and associated tradeoffs (Figure 3.4). It highlights the challenge of simultaneously reducing GHG emissions and limiting water consumption. Power production from solar PV and wind resources, for example, have the least carbon and water intensity but suf-

Figure 3.4. Effect of Emerging Technologies on Carbon and Water Intensity of Electricity Sources



Source: Lux Research, 2009.

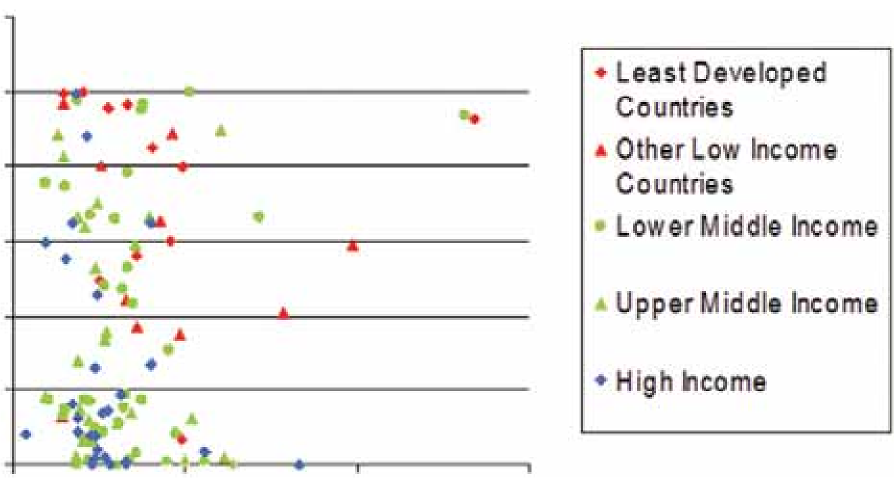
fer from intermittency, while nuclear power limits the carbon intensity and increases power output but requires significant amounts of water for cooling. Improvements in production efficiency and transmission design could help to reduce both carbon and water consumption.

Indicators of Energy Sector Vulnerability

When considering the state of a system, its development, and–most important—the need to adjust decisions, policies, and actions, measurement is key. Since climate variables can affect energy segments differently, mapping vulnerabilities according to these variables and analyzing the impacts on the whole energy system can offer a good measure of climate resilience. Historic information can also provide a basis on which to infer the effects of future climate variability according to current patterns of variability (Figure 3.5). This is especially relevant for the case of extreme weather events. Such indicators can help in vulnerability assessment by weighing the importance of specific energy segments in the whole energy system and by providing information about what climate variables are most likely to influence an entire energy system. However, creating a single metric for evaluating the resilience of a system to climate is challenging.

It can also be difficult to measure actual impacts of climate change and discern them from effects caused by natural (current) climate variability. Climate impact assessments are based on scenarios for future climate evolution that are usually constructed upon downscaled GCM runs. Using such climate scenarios and comparing energy system per-

Figure 3.5. Hydroelectricity Generation for Different Income Groups



Source: Authors' calculations based on data from WDI Online.
Note: Figure 3.5 presents countries distributed along axes that distinguish hydroelectricity as a share of all electricity generated, and the year-to-year variability of output per unit capacity. Low-income countries are overrepresented to the right and in the upper areas of the figure. A position in upper, right-hand area of the figure suggests that variability in hydropower output per unit of capacity has been the cause of relatively significant year-to-year fluctuation in the total national electricity supply from 1990 to 2006. Though there are many reasons for variable output, some benign, the figure suggests some linkage between variability in hydroelectricity production and a risk to national prosperity.

formance against current climate can create a set of indicators, but the extent to which these indicators represent the actual resilience of energy system is not clear.[33] Nevertheless, impact assessments based on downscaled GCM results provide a comprehensive set of scenarios for climate impact assessments. Furthermore, the use of a greater number of GCM runs can provide can provide a good measure of how resilient an energy system is to climate.

Therefore, a few indicators can be used to assess the resilience of a system based on a comparison of current and future climate. Resilience in resource endowments is mostly related to losses (or gains) in potential energy production, whereas resilience of energy supply depends also on the efficiency of energy production and conversion. In the first case comparing total available primary energy[34] in current climate against climate change scenarios provides a general measure of losses or gains. Analyzing specific energy segments (for example, hydropower, wind power, or oil reserves) is also important, especially when energy systems have limited diversity.

The level of diversification of energy production provides an important measure of resilience, as systems that heavily rely on a single energy source can be more exposed to climate impacts. The diversity of a system, on the other hand, does not allow for the use of a single indicator as a good measure of resilience. Still, many indicators[35] based on information about energy systems can be used to assess the extent to which those systems are vulnerable to climate change. In terms of energy diversification, the fuel shares in total primary and final energy supply, as well as total electricity production and installed capacity, can serve as indicators. Since renewable energy is more vulnerable to alterations in climate, the participation of renewable sources in total energy supply and electricity generation/installed capacity is also relevant in assessing climate resilience.

For energy supply, variations in overall system efficiency—measured, for example, by the ratio of total final to primary energy consumption—induced by climate change can indicate how energy conversion and transportation can be impacted by climate change. Although this measure can show aggregate impacts on energy supply, some measures for specific energy sources are needed to complement the understanding of the system's supply vulnerability. Projected climate change impacts on the renewable electricity generation capacity factor (assuming average and critical generation conditions) are a good measure for sources such as hydropower and wind power generation. Impacts on thermal (from fossil or nuclear) electricity generation, on the other hand, are better described in terms of conversion efficiency or capacity variations. Climate impacts on liquid biofuel production can be assessed through variations in agricultural and conversion productivity (for example, energy per planted area).

At the end of the energy chain, variations in a consuming sector's energy intensity assuming *ceteris paribus* conditions can portray a picture of vulnerability from the demand side. The biggest challenge here is conducting a strict *ceteris paribus* analysis in climate change assessments that are carried out for the long term. Finally, the level of information (both climate and energy) and knowledge about energy relations should be considered as an indicator of resilience, as it allows for better understanding and earlier action to adapt to climate change impacts.

A recent study by HELIO International (2009) looks at metrics for the vulnerability and resilience of energy systems and proposes a methodology (Box 3.2). It summarizes anticipated climate-induced impacts on key energy systems and outlines possible adaptation measures that take account of:

Box 3.2. Vulnerability Indicators (Sample)

Coal

- Number of coal mine plants located at less than 1 meter above sea level and within the area that could be flooded by a flood with a current recurrence period of 100 years

Oil and Gas

- Share of offshore oil and gas installations likely to be hit by a storm of more than 70 m/s gusts within the next 20 years (%)
- Share/number of refineries likely to be hit by a storm of more than 70 m/s gusts within the next 20 years (%)

All Fossil Fuels

- Number of thermal (coal, oil, and gas) power plants located at less than 1 meter above sea level and within the area that would be flooded by a flood with a current recurrence period of 100 years
- Additional information: expected number of droughts that lead to a capacity decrease of thermal power plants by more than 10% within the next 30 years

Hydropower

- Expected precipitation change over next 20−50 years (%) and/or probability of floods in each watershed
- Number of multiple-use dams in the country today: volume of water (m^3) for each dam
  - Describe what % of the water is used for: agriculture; power; drinking; additional information: expected additional runoff from glacier melting (million m^3)

Transmission Systems

- Length of in-country, above-ground transmission and distribution lines (km)
  - Distinguish between: high- (transmission); middle-, and low-voltage lines (distribution)
  - Describe any transnational lines
- Number and length of power cuts (differentiate between failures due to weather or equipment failure and those cuts due to rationing)
  - Average hours of interruption per year
- Percentage of energy supply requiring regional transport over 50 km
  - % that is transportation of fossil fuel
  - % that is transportation of biomass; if possible, comment on the informal sector

Biomass

- Proportion of biomass used for energy purposes (%) in total biomass production
  - If possible distinguish between different sources and different applications—agricultural biomass harvest; electricity; heat
  - Forest (as defined by the UN's Food and Agriculture Organization, FAO) biomass harvest: electricity; heat
- Expected precipitation change over next 20−50 years (%)
- Additional information: probability of temperature increase beyond biological heat tolerance of key biomass crops within the next 20 years (%)

Wind

- Number of wind turbines at less than 1 meter above sea level
- Projected change of average wind speed over the next 20 years, based on regional climate models (%)

Solar

- Capacity of solar installations already in place (m2)
  - Distinguish between PV (MW) and thermal (m2)
  - Ownership (private, government, public/private partnership, etc.)
- Expected temperature (°C) increase in the next 20 years relevant for PV capacity

Source: HELIO International, 2009.

- the capability of the energy system to resist damage and loss of function (technical);
- the organizational capacity, planning, training, leadership, experience, and information management to improve emergency-related organizational performance (civic/ organizational);
- the capacity of the managing enterprise to adapt in a timely fashion for post-disaster remediation, improvisation, innovation, and resources substitution (economic);
- the ability of decision makers to anticipate the effect/impact of the energy system on local ecosystems and ecosystem services (environment); and,
- the characteristics of the affected population and community that render social groups either more vulnerable or adaptable to energy-system-related disasters (social and cultural).

Observations and analyses from studies of 10 sub-Saharan African countries were chosen to test the vulnerability, adaptation, and resilience indicators. The region itself was chosen because of its vulnerability to climate change and its high level of energy poverty. The indicators cover all major energy systems.

Summary Table

This chapter attempted to cover a vast universe of impacts from changing climate conditions. Table 3.2 summarizes the impacts discussed in this chapter and provides an overview of the climate variables that are associated with them. This enables the reader to cross-reference the impacts of climate change on energy with the hotspots identified in Chapter 2, using the particularities of each region's energy system to identify the main vulnerabilities that could be expected in future climate change scenarios.

Table 3.2. Energy Sector Vulnerability to Climate Change

Item	Relevant climate impacts			Impacts on the energy sector
	General	Specific	Additional	
Climate change impacts on resource endowment				
Hydropower	Runoff	Quantity (+/-) Seasonal flows high and low flows Extreme events	Erosion Siltation	Reduced firm energy Increased variability Increased uncertainty
Wind power	Wind field characteristics, changes in wind resource	Changes in density, wind speed Increased wind variability	Changes in vegetation (might change roughness and available wind)	Increased uncertainty
Biofuels	Crop response to climate change	Crop yield Agro-ecological zones shift	Pests Water demand Drought, frost, fires, storms	Increased uncertainty Increased frequency of extreme events
Solar power	Atmospheric transmissivity	Water content Cloudiness Cloud characteristics		Positive or negative impacts
Wave and tidal energy	Ocean climate	Wind field characteristics No effect on tides	Strong nonlinearity between wind speed and wave power	Increased uncertainty Increased frequency of extreme events
Climate change impacts on energy supply				
Hydropower	Water availability and seasonality	Water resource variability Increased uncertainty of expected energy output	Impact on the grid Wasting excessive generation Extreme events	Increased uncertainty Revision of system reliability Revision of transmission needs
Wind power	Alteration in wind speed frequency distribution	Increased uncertainty of energy output	Short life span reduces risk associated with climate change Extreme events	Increased uncertainty on energy output
Biofuels	Reduced transformation efficiency	High temperatures reduced thermal generation efficiency	Extreme events	Reduced energy generated Increased uncertainty
Solar power	Reduced solar cell efficiency	Solar cell efficiency reduced by higher temperatures	Extreme events	Reduced energy generated Increased uncertainty
Thermal power plants	Generation cycle efficiency Cooling water availability	Reduced efficiency Increased water needs, for example during heat waves	Extreme events	Reduced energy generated Increased uncertainty
Oil and gas	Vulnerable to extreme events	Cyclones, floods, erosion and siltation (coastal areas, on land)	Extreme events	Reduced energy generated Increased uncertainty

(continued)

Table 3.2 (continued)

Item	Relevant climate impacts			Impacts on the energy sector
	General	Specific	Additional	
Impacts on transmission, distribution, and transfers				
Transmission, distribution, and transfers	Increased frequency of extreme events Sea level rise	Wind and ice Landslides and flooding Coastal erosion, sea level rise	Erosion and siltation Weather conditions that prevent transport	Increased vulnerability of existing assets
Impacts on design and operations				
Siting infrastructure	Sea level rise Increased extreme events	Flooding from sea level rising, coastal erosion Increased frequency of extreme events	Water availability Permafrost melting Geomorphodynamic equilibrium	Increased vulnerability to existing assets Increased demand for new good siting locations
Downtime and system bottlenecks	Extreme weather events	Impacts on isolated infrastructure Compound impacts on multiple assets in the energy system	Energy system not fully operational when community requires it the most	Increased vulnerability. Reduced reliability Increased social pressure for better performance
Energy trade	Increased vulnerability to extreme events	Cold spells and heat waves	Increased stress on transmission, distribution, and transfer infrastructure	Increased uncertainty Increased peak demand on energy system
Impacts on energy demand				
Energy use	Increased demand for indoor cooling	Reduced growth in demand for heating Increased energy use for indoor cooling	Associated efficiency reduction with increased temperature	Increased demand and peak demand, taxing transmission and distribution systems
Other impacts				
Cross-sector impacts	Competition for water resources Competition for adequate siting locations	Conflicts in water allocation during stressed weather conditions Competition for good sitting locations	Potential competition between energy and nonenergy crops for land and water resources	Increased vulnerability and uncertainty Increased costs

Source: Generated by authors.

Notes

1. Many studies investigate the relationship between energy and climate, but without focusing on global climate change.
2. The Andean nations (Colombia, Ecuador, Peru, and Bolivia) rely on mountain river basins for the provision of over 70 percent of their power for water supply systems and for agriculture.
3. Defined as the total annual energy that would be available if all runoff at all locations were to be harnessed, without losses, down to the sea level (Lehner et al., 2005), which is directly calculated from elevation and water availability.
4. Wind energy can be a low-carbon alternative to fossil fuels. There is significant remaining potential for increased wind generation that is broadly competitive with other generation sources (Blanco, 2009).
5. Around 1,000 ppm for most plants.
6. Such studies have an additional layer of uncertainties related to economic parameters, such as costs, discount rates, electricity prices, and so forth.
7. Firm power can be defined as the amount of energy the hydropower system can produce under critical conditions, defined by the level of reliability expected from the entire system. In some extreme cases the worst historical hydrological conditions have been used.
8. Technologies such as pumped storage water reservoirs can be used for this purpose.
9. These studies concentrate on the impact of different wind velocities on electricity generation from wind turbines. Other climate variables that can affect wind power (such as temperature and humidity that can impact air density, as well as ice formation on turbines blades) have not been thoroughly assessed.
10. Site-specific research is needed to obtain better information about the probability density function of wind speed, which is essential to project wind power generation.
11. Net energy value: measurement of the energy gain and sustainability of bio-ethanol and other biofuels. It is the difference between the ethanol and co-product outputs and the nonrenewable input energy requirements.
12. In fact, much has been discussed about possible effects of climate change on ENSO behavior. For a more detailed analysis, see Paeth et al. (2007).
13. Geothermal energy production is basically affected by cooling efficiency.
14. Weighted average that captures the total thermoelectric water withdrawals and generation for both once-through and recirculating cooling systems.
15. Water consumption refers to the amount of water that does not go back to the original source, and water withdrawal concerns the total amount taken from its original source.
16. There are two main types of cooling systems: once-through systems (open loop), which require more withdrawals, but with less consumption levels; and recirculating systems (closed loop), which have reduced withdrawals but bigger consumption levels.
17. Assumes that additional generation needed to run the CCS operation is delivered by more water-cooled coal generation.
18. It should be noted that the power plant with closed-circuit cooling system analyzed in the study uses mine water, with temperature approximately equal to groundwater temperature. This means that climate change wouldn't affect significantly the water temperature, not affecting the water demand.
19. For example, Melting Arctic: Bering Strait is the next Panama Canal (Longshore & Shipping News, 2010).
20. Nine European countries (the United Kingdom, Germany, France, Belgium, the Netherlands, Luxembourg, Denmark, Sweden, and Ireland) have signed a major agreement to develop the world's first large-scale offshore wind energy grid to offer weather-proof supply from renewable energy in the North and Irish seas, thus providing a boost to the continent's fast-expanding offshore wind industry. The project is expected to cost €30 billion. See also: http://www.guardian.co.uk/environment/2010/jan/03/european-unites-renewable-energy-supergrid.
21. Western wind and solar integration study (2010) prepared for the National Renewable Energy Laboratory by GE Energy (GE Energy, 2010).

22. Eastern wind integration and transmission study (2010) prepared for the National Renewable Energy Laboratory by EnerNex Corporation (EnerNex, 2010).
23. http://www.euei.net/wg/african-renewable-energy-technology-platform-afretep.
24. This would involve transmission lines between South East Asia and Australia; http://www.desertec-australia.org/.
25. Exajoule (EJ) = 10^{18} Joule.
26. According to different studies, the range for the base temperature is given as 18–22°C.
27. $Q = m \cdot c \cdot \Delta T$
28. The shortage of studies is, in part, a consequence of the difficulty to collect data and to develop models for different services at the global scale.
29. It should be noted that sea level rise may be permanent in some places, not being restricted to extreme events.
30. Some hydraulic approximations rate sediment transport proportional to the discharge to the seventh power, highlighting the profound impact few large hydrographs have in the annual sediment load.
31. For example, Laakso et al. (2003) indicate that icing may be responsible for 9 to 45 percent of wind turbines downtimes in Finland.
32. Damages to structures are not considered here, only the need to shut down turbines due to extreme high wind.
33. This is especially relevant for the case of extreme weather events.
34. In this case, a differentiation between stocks and fluxes is needed.
35. The indicators presented here were based on the Energy Indicators for Sustainable Development proposed by the International Atomic Energy Agency (IAEA, 2005).

CHAPTER 4

Emerging Adaptation Practices

Identifying energy sector vulnerabilities to the consequences of climate change is essential for the formulation of adaptation policies, while, at the same time, the impacts of climate change on the energy sector can affect the evaluation of technological alternatives and the formulation of the energy policy of a country (Wilbanks et al., 2007).

In the global climate change context, adaptation requires a combination of elements that include the availability of economic and natural resources, access to technology and information, and infrastructure and institutions (Smit et al., 2001). Adaptation measures can be taken as a response to climate change alone, as part of a broader set of initiatives (Adger et al., 2007), or as an addition to baseline investments for the purpose of increasing resiliency. There are similarities between adaptation (in the climate change context) and measures taken by individuals, firms, or governments to deal with the natural (current) climate variability and the variability created by global climate change (Callaway, 2004). Therefore, dissociating climate change adaptation from energy policy can be complicated, especially when there are many no-regret actions.

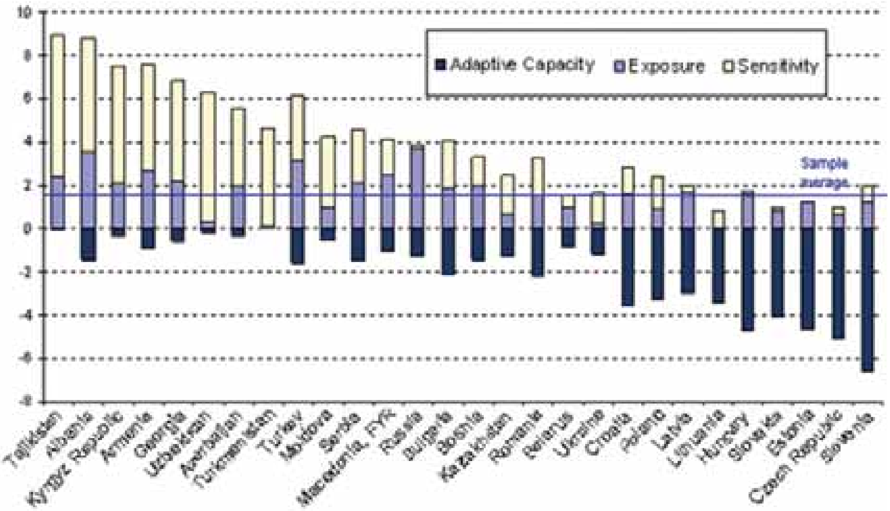
Energy systems already take account of some climate risks in their operation and planning.[1] Adaptation measures can further reduce system vulnerability to environmental change, by building capacity and improving information for decision making, and integrating climate risks into management and operational decisions. Adaptation measures that fall into this general category span improvements in weather/climate information; the coupling of climate and energy analysis by adapting climate data to energy system needs; addressing current inefficiencies in the use of available resources; and energy sector diversification. Many actions increase a system's resilience to variations in climate, regardless of global climate change, and can be implemented at relatively low cost, since adaptation may have associated external benefits.[2]

Typology of Adaptation Responses

The main objective of adaptation as defined by the IPCC is "*to moderate harm or exploit beneficial opportunities*" (IPCC, 2007b). In the case of the energy system, the primary objective of adaptation could be interpreted as guaranteeing the supply of energy, and balancing production and consumption throughout time and space.

The process of adapting to climate change is complex and consists of a multitude of behavioral, structural, and technological adjustments. Several typologies of adaptation measures have been proposed that provide some useful distinctions to support a discussion of the nature of adaptation processes and their forms. Here we differentiate adaptation measures based on a set of attributes used in studies by Burton et al. (1993), Stakhiv (1993), Carter et al. (1994), Smit et al. (1999, 2000), UKCIP (2007), and the OECD (2008):

Figure 4.1. Vulnerability Index, an Example from Europe and Central Asia



Source: World Bank, 2009d.
Note: The extent to which countries are vulnerable to climate trends is driven not just by their exposure to change but also by their sensitivity to an event, which is exacerbated by past practices, socioeconomic, or legacy issues. The degree to which this vulnerability affects a country's economy is driven by its coping or adaptive capacity. This relationship is demonstrated for countries in Europe and Central Asia.

- Based on the *timing* of an action, adaptation measures may be *proactive* or *reactive.* A proactive approach in energy systems aims to reduce exposure to future risks. A purely reactive approach aims to alleviate impacts on installed technologies/supply systems, for instance, reinforcing existing energy infrastructure with more robust control solutions that can better respond to extreme-weather-related service interruption.
- Based on the *temporal scope*, adaptation measures can be *short term* or *longer term.* This distinction can also be referred to tactical versus strategic, or to instantaneous versus cumulative (Smit et al., 1999). In the natural hazards field it is referred to as adjustment versus adaptation (Smit et al., 2000). The distinction between short-run and long-run adaptation has to do with the pace and flexibility of adaptation measures.
- Based on their *ability to face associated uncertainties and/or to address other social, environmental, or economic benefits*, adaptation measures can be *no-regrets* options (see Box 4.1), *low-regrets* options, or *win-win* options. No-regrets adaptation measures are those whose socioeconomic benefits exceed their costs, whatever the extent of future climate change. Low-regrets adaptation measures are those for which the associated costs are relatively low and for which the benefits under projected future climate change may be relatively large. Win-win adaptation measures are those that minimize social risk and/or exploit potential opportunities but also have other social, environmental, or economic benefits.

Box 4.1. No Regret Actions: Some Examples

Monitoring climate. An important measure to reduce vulnerability to climate change is improving regional climate databases. In many regions, climate data availability is coarse or restricted to interpolations between distant measurement points. Improving the climate database is important not only to increase forecast capacity and help with operational planning, but also to develop tools that can translate GCM long-term projections into global or regional impacts. Moreover, a good climate database is crucial to monitor climate events and the evolution of climate variables in a global climate change context.

Modeling climate. Climate impact assessments rely on climate variables projected from downscaled results of GCMs as scenarios for evolution of the future climate. Energy models that convert alterations in climate variables into energy impacts need to use another set of modeling tools that help translate raw climate variables into those used in energy analysis. For example:

- climate data on precipitation and temperature must be converted into river flows at specific points to be able to assess climate impacts on hydropower;
- specific sites, such as power plants, need to be geo-referenced and cross-referenced with temperature projections to be able to evaluate possible losses in efficiency; and
- future climate conditions as modeled need to be used as inputs in hydrology tools to be of use in the projection of impacts for hydropower.

It is therefore important to create interfaces that allow climate model outputs to be linked with energy model inputs, as well as to develop specific methodologies when necessary. In the case of wind energy analysis, for example, the probability distribution of wind speed is essential for projecting climate impacts on the amount of energy produced from a wind turbine. Climate projections from GCMs and downscaling techniques are not suited to produce such information (Pryor and Barthelmie, 2010), hampering wind energy climate impact assessments.

Source: Authors.

- Adaptation measures can be *localized* or *systemic*. Impacts from climate change are frequently local, such as the impacts of sea level rise on energy infrastructure in coastal areas. But there are also instances where the impacts are systemic, such as when climate impacts affect resource endowments. However, even under local conditions, for measures to be implemented, most often they must also be supported by national or even international policies and strategies (Appendixes G and L).
- Based on the *nature of agents involved in the decision making*, adaptation measures can be *private* or *public*. Note that this distinction can also be referred to as autonomous or “market-driven” versus planned or “policy-driven” adaptation. Most of the energy infrastructure in developed countries is privately owned, but since these economies depend significantly on reliable supplies of energy, a role exists for governments to ensure that this energy infrastructure is resilient to climate change. Under an integrated planning approach, adapting to this effect through energy demand management would be preferable to force suppliers to increase generation from a coal- or gas-fired power plant.

The following sections explore these concepts in the context of the energy sector and three main themes: (i) building adaptive capacity, (ii) delivering adaptation actions, and (iii) agents of adaptation, as summarized in Table 4.1.

Table 4.1. Categories of Adaptation Measures in the Energy Sector

Building adaptive capacity
Improved knowledge system
Data collecting and monitoring, research, and awareness raising
Supportive framework for action
Enhancing the capacity of local institutions, working in partnerships, and supportive public governance
Delivering adaptation actions
Preventing effects or reducing risks
Relocation of activities
Climate-proofing of infrastructure
Introduction of multiple land-use strategies that account for climate risks
Implementation of emergency, contingency, and disaster planning
Sharing responsibility for losses or risks
Insurance
Diversification of energy sources
Exploiting opportunities
Demand-side management
Decentralized energy structure
Urban design and land-use planning

Source: Adapted from UKCIP, 2007.

Building Adaptive Capacity

Adapting to climate change has to be understood as an ongoing process. A critical step in ensuring energy system resilience is to build adaptive capacity, defined as "*the ability or potential of a system to respond successfully to climate variability and change*" (Adger et al., 2007). It reflects fundamental conditions such as access to information (research, data collecting and monitoring, and raising awareness), and institutional development (supportive governance, partnerships, and institutions).

Improving Knowledge

Generating data and knowledge is a necessary condition for effective action.

On the research side, Wilbanks et al. (2008) stress the need to expand the knowledge of climate change impacts on energy production and use. They enumerate some general needs as well as needs related to major technology areas. Examples of general needs include:

- Provide higher-resolution models for local and small-regional impact evaluation where most energy facility decisions operate.
- Research the technologies and practices to save cooling energy and reduce electrical peak load demand.
- Research how the changing regional patterns of energy use impact regional energy supply, institutions, and consumers.
- Better understand the effect of changing climate conditions on renewable and fossil-based energy development and market penetration and associated impacts on regional energy balances and economies.

For technology, six research priorities are proposed:

- Better understand space cooling efficiency potential.
- Improve information on the interaction between water demand and use.
- Improve understanding of climate change impacts and local variability on wind and solar energy production.
- Develop strategies and improve the technological potential of energy supply systems.
- Understand the role of regional interconnections and distributed generation in improving the resilience of electricity supply systems.
- Understand the impact of severe weather events on sub-sea pipeline systems, especially in the Gulf of Mexico, and develop strategies to reduce such impacts.

Data collection and monitoring are also important elements of a capacity-building strategy. It is often stated that "you cannot manage what you cannot measure"; whatever the validity of that statement, when handling hydro-meteorological/climate risks, apposite information is indispensable: *"People do not know when there is rain in the mountains. It is only when the tributaries rise that people are caught unaware"* (IRIN, 2009). The tragic Panay floods of 2008 similarly caught populations oblivious to the risks because of a lack of real-time rainfall monitoring in the mountains.[3] Information requirements are not merely real time, but also include assessment, monitoring, and prediction appropriate to risks.

Climate adaptation measures in the energy sector are critically dependent on reliable and timely weather and hydro-meteorological observations combined with forecast models (for example Numerical Weather Prediction models) and assessment tools specific for the energy sector (Troccoli, 2010a). Ready and reliable access to data and forecasts of some weather, hydro-meteorological, and climate services could be facilitated using grid computing technology. This would be particularly useful for small companies in the energy sector and would serve the regulatory and scientific communities undertaking climate/energy research. The establishment of the National Oceanic and Atmospheric Administration (NOAA) Climate Service announced in February 2010 (NOOA, 2010a) is an example of an information facilitation initiative (see Chapter 5).

Experts also stress the importance of assuring consistency with the data used in energy demand and production models. Small errors might be amplified by the transfer models to unacceptable levels.

Awareness. Though risk management practices are professionally handled in most cases, many hydro-meteorological/climate-adaptation-related risks fall well below the "radar" in the energy sector. For a variety of reasons—limited vision, short-term opportunism, simple lack of knowledge, or other factors—adaptation needs are unlikely to be included among risks and vulnerabilities unless managers are fully aware of the issues and have developed and commissioned processes to incorporate climate adaptation into risk management. Without awareness and the incentive to act, the dangers are self-apparent: *"A severe drought has forced Venezuela President Hugo Chavez to ration electricity in South America's top oil exporter, but underinvestment and short-sighted planning during an economic boom are as much to blame as the weather"* (Reuters, 2010).

This situation may be addressed through appropriate programs of awareness building together with the development of essential information sources and delivery. Both aspects might be instigated synergistically with other programs or sectors.

The knock-on effect of failing to address these risks may include negative feedbacks: *"In Iran in 2009: * Electric power stations—that need water to make steam—had to be shut down because of the lack of water. * Electricity shortages dried crops for lack of power to pump water along irrigation channels. * For lack of electricity, people chopped firewood which eroded the landscape yet more, causing more drought"* (Ecolocalizer, 2009).

Providing a Supportive Framework for Action

It is equally important to link climate knowledge with action and persuade businesses, communities, and individuals to adjust their behavior in ways that promote adaptation and limit emissions (UNEP, 2006). This requires information to be relevant, technically sound, and user-oriented. Successful adaptation involves collaboration across a multitude of interested partners and decision makers: international, national, and local governments, the private sector, nongovernmental organizations and community groups, and others, who all have important roles to play. For example, it is critical to facilitate dialogue between weather-water-climate scientists and energy decision makers to address cross-cutting issues for energy production, access, and efficiency. Governments, public institutions, and businesses can all contribute to an adaptive response, as described next.

National and transnational governments can provide a clear policy framework to guide effective adaptation in the medium and long term. In particular, these governments can support the provision of high-quality climate information, the establishment of land-use plans and performance standards, the definition of long-term policies for climate-sensitive public goods such as coastal protection or emergency preparedness, and the provision of safety nets for those least able to afford protection and/or insurance.[4]

Local public institutions (local governments and agencies), *civil society institutions* (producer organizations, cooperatives, savings and loan groups), and *private institutions* (NGOs and private businesses that provide insurance or loans) have an important operational role (Agrawala and Fankhauser, 2008) given that adaptation action is inevitably mainly local. The involvement of local institutions is therefore critical to the planning and implementation of adaptation policies and projects. Connor et al. (2005) have reported some recent efforts by European countries legislating and creating councils of energy users to work side by side with national energy boards or regulatory bodies. Box 4.2 provides examples of localized adaptation.

At the **business** level, Sussman and Freed (2008) note that *"business efforts to address the potential risks posed by the physical effects of climate have in general lagged behind consideration of the financial risks associated with mitigation."* A report recently released by the Carbon Disclosure Project (CDP, 2007) indicates that nearly 80 percent of the 500 corporate respondents considered climate change to present some sort of commercial risk but were more concerned about risks associated with regulations and higher energy prices (resulting from mitigation efforts) than the physical effects of climate change. However, energy companies with significant operations in areas vulnerable to extreme weather events (such as the Gulf Coast of the United States) consistently listed physical risks as a concern. Some businesses have thus been forced to recognize the need for immediate/reactive adaptation and are even contemplating proactive adaptation to expected future changes.

Box 4.2. Examples of Localized Adaptation

- Measures to address sea level rise in coastal areas, affecting the location of energy infrastructure. For example, significant energy infrastructure sits in the Gulf of Mexico (both in the United States and Mexico) and in coastal areas of the Caribbean Sea. The gradual increase in sea level rise has the potential to upset the normal operation of these facilities. The best long-term adaptation measure is the relocation of existing infrastructure or revised land zoning for green fields. Alternatively, barriers against flooding caused by sea level rise may be required.
- Measures to address the intensification of weather extremes that may affect the specific location of energy exploration, transport, or production facilities. Intensification of hurricanes or increases in the frequency of tropical storms in coastal areas will affect the level of protection and location of specific infrastructure. As is the case for actions to address consequences from sea level rise, relocation may be the most cost-effective alternative for green fields. Increasing the resilience of construction is also an alternative. For Saint Lucia in the Caribbean, the World Bank is supporting the development of construction codes in coastal infrastructure that could prevent severe damage in the case of intense winds.
- Measures to address changes in the water table caused by sea level rise in coastal areas or permafrost levels due to melting ice in northern latitudes or at high altitudes. Changes in water tables will affect the use of water and the risk of flooding in areas where energy infrastructure is located. Changes in permafrost will affect the structural footings of production and transport infrastructure. Besides relocation, alternatives would include the strengthening of foundations for green-field facilities and the siting of pylons for pipes.
- Measures to address changes in sea surface and air temperature that affect the water intake rates or ratings for cooling towers and heat exchangers. In a landfill-gas power plant in Monterrey, the rating of heat exchangers of the compressors had to be modified to account for higher-than-historical daytime temperatures during the summer months. This was achieved by increasing the heat exchange surface area to prevent a reduction in the efficiency of the compressors. Cooling towers could also be designed with higher heat exchange areas to address the reduced delta in temperatures.

Source: Authors.

Delivering Adaptation Actions

Adapting to the Consequences of Climate Change or Reducing Risks

Certain short- and medium-term effects of climate change will be almost unavoidable (IPCC AR4), and one focus of adaptive actions should therefore be to alleviate or minimize these negative effects. The high vulnerability of energy infrastructure to environmental change is due largely to its long life span, especially where impacts related to climate change were not factored in at the design stage. Long-lifespan infrastructure, such as hydropower plants, is generally less adaptable to changes in actual facilities[5] whereas short-lifespan infrastructure can be replaced in the long term as the climate changes. Paskal (2009) offers some examples of this assertion: *"The Hoover Dam in western United States was completed in 1935 and is still an important hydroelectric generator. China's Three Gorges Dam, which is not fully operational, has an expected lifespan of at least fifty years. Nuclear power stations, from design through to decommissioning, may be on the same site for a hundred years."*

Adaptation responses can be categorized as: technological, behavioral, or structural. **Technological responses** invest in new or adapted technologies to reduce the vulnerability of energy assets or strengthen their resilience to the consequences of global warming. Some responses include:

- **Physical protection** such as targeted retrofitting of existing infrastructure to address increases in exposure to climate impacts in coastal zones (reinforcing physical assets exposed to increases in high intensity winds or located in flood zones). Targeted refurbishing can help to increase the robustness of weaker elements of energy assets with typical life spans of several decades. Other examples include protective infrastructure actions like improving the robustness of offshore installations that are vulnerable to storms, building dikes and desilting gates, increasing dam heights, and enlarging floodgates.
- **Better design** of assets in the planning stage through improved design standards. Current or anticipated increases in vulnerability can be addressed through adapted design or revamped standards to increase the resilience of new infrastructure. One example is the revision of structural footings for new pipeline distribution systems in areas where permafrost can no longer be considered to be constant.[6] Deeper pilings can be used, and buildings can be raised slightly above the ground and thickly insulated. Lighter-weight building materials can also be employed to limit subsidence and shifting during thaws. Another example is the application of new weight loads for high voltage transmission towers in areas that are exposed to increases in the intensity of winter precipitation or winds.
- **New technologies**. An effective adaptation response may also require the deployment of new technologies. One example is the development of smart grids to accommodate renewable sources with intermittent generation in existing grids. This requires novel relay techniques to ensure the stability of the power network.

Behavioral responses. An option to adapt energy infrastructure to climate change is to re*consider the location* of investments. As already mentioned the concentration of energy infrastructure along the Gulf Coast could be particularly costly if climate change leads to more frequent and intense storm events, and it could be in the interest of energy producers to shift their productive capacity to safer areas.[7] Note that, as Paskal (2009) mentions, substantial investments in new emerging infrastructure are likely to take place in the next decades as a result of scheduled decommissioning, revised environmental standards, stimulus spending, and new development.[8] Location decisions for these new investments should take account of the impact of a changing environment.

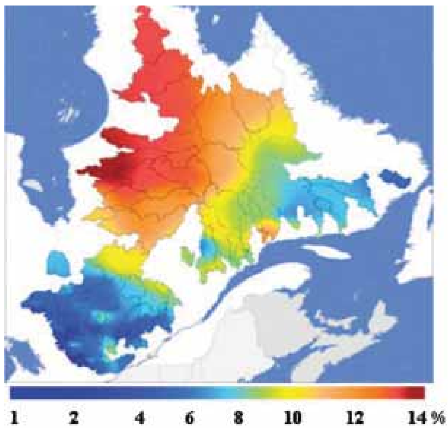
Anticipating the arrival of a climate hazard by using improved meteorological forecasting tools or better communication with meteorological services, or by revising HAZOP studies to accommodate emerging climate risks are other examples of behavioral strategies. Changes in the operation and maintenance of existing infrastructure are also behavioral adaptation strategies. Some examples include actions to manage on-site drainage and runoff of mined resources, change coal-handling processes due to increased moisture content, and adapt plant operations to changes in river flow patterns (Box 4.3).

All of these measures require future climate risks to be mainstreamed into decision-making processes, including relevant policy interventions, planning, and management decisions. This means that decision makers must consider future climate projections when making decisions about coastal land-use planning, hazard management, or emergency preparedness, and that these policies and plans should be regularly updated and upgraded.

Box 4.3. Adapting Quebec's Hydroelectric Production to Climate

Regions and countries reliant on hydropower for their energy supply have been especially concerned about climate change for a reason. Hydropower runs on water, and its availability is changing with the climate. A prime example is the province of Québec in Canada. Hydropower supplies 97 percent of its energy needs with about 36,000 MW of installed capacity.

Preparing for climate change through adaptation. Extensive work has been undertaken by Hydro Québec over the past decade to map climate change impacts. To assess the changes in runoff, and thereby hydroelectric production, a conceptual lumped hydrological model (made for the Fourth Assessment Report of the IPCC) was used to analyze 80 climate projections for nearly 100 watersheds in the region. The results show that the region will see an increase in annual runoff, ranging from 1 to 15 percent, along with changes in seasonal water variability and increased probabilities of droughts and floods. The figure below shows estimated annual changes in the watersheds.



Source: Hydro Quebec.

High price for inaction. A further study mapped the impacts of change on hydropower production for 10 different future hydrological conditions. A simulation of the power yield for the Peribonka River system was made for two scenarios (business as usual and one where adaptive measures are taken). The results show that the price of inaction is high, with a reduced hydropower output of about 14 percent, while adaptation action could increase hydroelectric production by about 15 percent (Minville et al., 2009, Pacher et al., 2009).

Source: Authors.

Table 4.2 offers examples of technological and behavioral adaptation measures in the energy sector intended to minimize negative impacts due to long-term changes in meteorological variables and extreme events. The third adaptation category is structural.

Structural responses include all actions requiring sector wide changes, including the deployment of sector wide incentives. One example is the adoption of policy frameworks to facilitate the internalization of adaptation concerns in energy systems, either through the set up of economic or fiscal incentives.

The development and adoption of tools to hedge the costs of protecting energy infrastructure if a disaster does strike (Appendix F) is another form of structural response. For example the Deepwater Gulf of Mexico Pipelines Induced Damage Characteristics

Table 4.2. Examples of Adaptation Measures to Reduce Losses/Risks in Energy Systems

ENERGY SYSTEM		TECHNOLOGICAL		BEHAVIORAL		
		"Hard" (structural)	"Soft"(technology and design)	Re(location)	Anticipation	Operation and maintenance
SUPPLY	MINED RESOURCES (inc. oil and gas, thermal power, nuclear power)	Improve robustness of installations to withstand storms (offshore), and flooding/drought (inland)	Replace water cooling systems with air cooling, dry cooling, or recirculating systems Improve design of gas turbines (inlet guide vanes, inlet air fogging, inlet air filters, compressor blade washing techniques, etc.) Expand strategic petroleum reserves Consider underground transfers and transport structures	(Re)locate in areas with lower risk of flooding/drought (Re)locate to safer areas, build dikes to contain flooding, reinforce walls and roofs	Emergency planning	Manage on-site drainage and runoff Changes in coal handling due to increased moisture content Adapt regulations so that a higher discharge temperature is allowed Consider water re-use ad integration technologies at refineries
SUPPLY	HYDROPOWER	Build de-silting gates Increase dam height Construct small dams in the upper basins Adapt capacity to flow regime (if increased)	Changes in water reserves and reservoir management Regional integration through transmission connections	(Re)locate based on changes in flow regime		Adapt plant operations to changes in river flow patterns Operational complementarities with other sources (for example, natural gas)
SUPPLY	WIND		Improve design of turbines to withstand higher wind speeds	(Re)locate based on expected changes in wind speeds (Re)locate based on anticipated sea level rise and changes in river flooding		
SUPPLY	SOLAR		Improve design of panels to withstand storms	(Re)locate based on expected changes in cloud cover	Repair plans to ensure functioning of distributed solar systems after extreme events	
SUPPLY	BIOMASS	Build dikes Improve drainage Expand/improve irrigation systems Improve robustness of energy plants to withstand storms and flooding	Introduce new crops with higher heat and water stress tolerance Substitute fuel sources	(Re)locate based on areas with lower risk of flooding/ storms	Early warning systems (temperature and rainfall) Support for emergency harvesting of biomass	Adjust crop management and rotation schemes Adjust planting and harvesting dates Introduce soil moisture conservation practices
DEMAND		Invest in high-efficiency infrastructures and equipment Invest in decentralized power generation such as rooftop PV generators or household geothermal units		Efficient use of energy through good operating practice		
TRANSMISSION AND DISTRIBUTION		Improve robustness of pipelines and other transmission and distribution infrastructure Burying or cable re-rating of the power grid		Emergency planning	Regular inspection of vulnerable infrastructure such as wooden utility poles	

Source: Adapted from HELIO International, 2009.

and Repair Options (DW RUPE) project (Stress Subsea, Inc. 2005) is a joint industry study with the U.S. Minerals Management Service that is looking at the design of repair plans to ensure distributed solar systems can function after extreme events.

Sharing Responsibility for Losses or Risks

Preventing losses/risks is not the only way to adapt. The energy sector can share responsibilities for losses and risks by hedging weather events or diversifying the energy mix.

Hedging Weather Events. In finance, a hedge is a position established in one market in an attempt to offset exposure to price fluctuations in some opposite position in another market with the goal of minimizing one's exposure to unwanted risk. More specifically, the weather risk market makes it possible to manage the financial impact of weather through risk transfer instruments based on a defined weather element, such as temperature, rain, snow, wind, and so forth Weather risk management is a way for organizations and/or individuals to limit their financial exposure to disruptive weather events.

Energy is a sector (among many others) whose operations and profits can be significantly affected by the weather: unexpected weather events can cause significant financial losses. Use of financial instruments such as weather derivatives (typical of high-probability events, for example, a warmer-than-normal winter) and insurance (for low-probability but catastrophic events, for example, hurricanes) provides a means for clients to protect themselves against adverse financial effects due to variations in weather/climate (Box 4.4).

The end users of weather derivatives include a wide range of companies from diverse industries. The Weather Risk Management Association, or WRMA, is the industry body to which most underwriters of weather risk, as well as many end-user customers, belong. Primary end-user segments for weather derivatives relevant for the energy sector include local distribution companies of natural gas, electric utilities, propane and heating oil distributors, offshore production rig operators, the transportation industry, and a range of manufacturing firms. According to a 2006 survey carried out by PricewaterhouseCoopers, almost 50 percent of inquiries about weather risk instruments was made by users in the energy industry (down from about 70 percent in the previous year) (WRMA, 2006).

As an example, natural gas company managers concerned with customer satisfaction attempt to minimize the occurrence of extreme bills by means of exchange-traded weather derivatives, which provide a way of hedging exposure to increases in the quantity of gas demanded during colder-than-expected winter months. For instance, Leggio and Lien (2002) found that consumer exposure to extreme bills is minimized when the utility uses pricing and weather derivatives.

Hedging weather is more predominant in the developed world, however. For example, in the developing world less than 2 percent of the costs of catastrophes in general are absorbed by any form of insurance, compared to 50 percent of the costs of catastrophes covered by insurance in the United States (IIASA, 2010).

Specifically for weather, insurance schemes designed to help shield small farmers from the impact of natural disasters and climate change have been introduced in recent years under the leadership of the World Food Programme (WFP). Weather-index-based insurance schemes have been successfully piloted in a number of countries, including Ethiopia, Malawi, Nicaragua, Honduras, and India. Payouts to farmers who subscribe to

Box 4.4. Weather Coverage and Insurance Instruments

Loans and technical assistance programs could be complemented by weather coverage and insurance instruments that could help mitigate the anticipated losses associated with climate variability and extreme events. Weather coverage is an emerging market instrument that pays on the basis of a measurable weather event and does not require individualized loss assessment (as in the case of more traditional insurance). Customized weather coverage is being used by hydroelectric utilities in Australia, the United States, India, and Canada to do the following (WeatherBill 2009):

- *Stabilize revenues* and protect against income loss due to precipitation or temperature fluctuations affecting power generation.
- *Control costs* associated with power purchases to address supply shortages arising from weather-related events (for example, below-average precipitation).
- *Manage cash reserves*, for example, to ensure that reserve funds are not required to cover operating costs when budgets are stressed due to successive drought years.

Such instruments can be accessed on the insurance market. The World Bank Group (WBG) also offers a range of services to mitigate the impacts of disasters and weather events:

- **Catastrophe Risk Deferred Draw-down Option**, a deferred development policy loan offering IBRD-eligible countries immediate liquidity up to US$500 million or 0.25 percent of GDP (whichever is less) if they suffer a natural disaster.
- **Sovereign Budget Insurance**, advisory services to help countries access the international catastrophe reinsurance markets on competitive terms; currently used by 16 Caribbean countries as parametric insurance against major hurricanes and earthquakes.
- **Insurance Linked Securities**, a multi-country catastrophe bond to poll the risks of several countries and transfer the diversified risk to capital markets is under development. WBG has experience in working with Mexico to transfer earthquake risk to investors through such mechanisms (2006).
- **Catastrophe Property Insurance**, to create competitive insurance markets and increase catastrophe insurance penetration.
- **Indexed-Based Weather Derivatives.** In Malawi the World Bank provided intermediation services on an index-based weather derivative. If precipitation falls below a certain level, a rainfall index reflects the projected loss in maize production, and payout is made when production falls significantly below historic averages.

Source: Adapted from World Bank, 2009e.

the schemes are triggered by pre-defined and independently verifiable indices tracking events such as lack of rainfall during critical crop growing periods. Weather-indexed insurance has also been piloted by WFP as the basis for the first humanitarian insurance policy for Ethiopia (Medical News Today, 2008).

To manage insurance schemes for developing countries, the Weather Risk Management Facility (WRMF), a joint International Fund for Agricultural Development (IFAD) and WFP initiative with the Bill & Melinda Gates Foundation, has been launched to support the sustainable development of weather risk management instruments in developing countries (IFAD, 2010). Although the initial focus is on agriculture and food security, this would appear an ideal platform for weather-indexed insurance for the energy sector as well.

Although not directly related to hedging weather events, another insurance tool specifically for energy is available. Munich, RSA Insurance Group (RSA), and CarbonRe, with support from the Global Environment Facility (GEF) and the United Nations Environment Programme (UNEP), have recently launched an innovative mechanism for insuring renewable energy projects in developing countries. The global renewable energy insurance facility[9] offers standard and customized insurance solutions for renewable energy projects in developing countries (WeatherBill Inc., 2009; World Bank 2008, 2009e, 2009f).

Diversifying Energy Systems. The level of diversification of an energy system has a profound influence on its resilience to climate impacts. Having alternative means to produce energy can reduce the vulnerability of the sector as a whole to a specific set of climate impacts (for example, hotter or dryer climate). On the other hand, relying on a single source of energy can render an energy system vulnerable in the case of an adverse impact from climate change. Energy security issues (not only in the climate change context) are therefore closely related to the level of diversification of an energy system. Broadening the range of power plant types and fuels in the generation mix and using a mix of centralized and decentralized supply patterns will help to increase the flexibility of the system and its resilience to more variable climatic conditions (Rothstein et al., 2006). An adaptation response may require a policy decision to diversify away from hydropower. This may represent an increase in the carbon footprint of the sector unless other renewable options can be deployed.

Power sector diversification can help address impacts on surface hydrology or precipitation patterns induced by climate change, for example, such as the impacts felt by countries in the Northern Andes that are heavily dependent on hydropower for electricity generation. Here climate impacts may affect the capacity of the hydropower system to store water by lengthening periods of drought or changing rainfall patterns due to oscillations in differential sea surface temperatures between the west and east Pacific. Albania is also vulnerable to the anticipated decrease in precipitation rates associated with future climate projections. Over 90 percent of domestic electricity generation today is dependent on hydropower, and the system has a low level of diversification (Appendix G).

Karakezi et al. (2005) identify the lack of diversification of energy sources in East Africa as of particular concern. The study notes that East Africa relies on hydropower for almost 80 percent of its electricity. A combination of increased drought and shorter rainy seasons is already causing frequent disruptions in power sector operation, and the main response is to turn to emergency thermal electricity that is often excessively costly and can have crippling effects on an economy. The authors claim the need to adopt more robust, resilient, and well-thought-out plans for dealing with drought-induced power crises. The study notes three essential elements for future planning: diversifying generating sources—using a wider mix of energy sources, promoting proven renewable energy technologies for electricity generation, and setting targets for renewables in the energy mix. HELIO International (2007) also conclude that energy development for Africa will require greater emphasis on small-scale, decentralized, and diversified supply.

Exploiting Opportunities

Sometimes adaptation can result in a win-win outcome; that is, it provides the "double dividend" of reducing the impact of climate change and improving some other dimension of our well-being.

Energy/water saving and demand-side management measures provide a cost-effective, win-win solution for mitigation and adaptation concerns in a context of rising demand and supply constraints, as they have the potential to reduce the stress on energy delivery systems. Adapting to variations in building energy demand involves: reducing energy demand (especially) for cooling; and for the specific case of electricity, compensating for impacts that coincide with peak demand (demand-side management; Box 4.5).

On the demand side, Hekkenberg et al., (2009) have identified a number of developments that may alter the need for heating or cooling. For instance, to reduce the need for cooling, actions could be taken to increase cooling efficiency, decrease internal heat gains (for example, from less use of electric appliances), and change patterns of human comfort. Also, opting for smaller residential and commercial spaces can reduce the energy needed for cooling (or heating). Complementary building design and construction practices can help maximize the use of natural light and ventilation through, for example, building shading techniques, windows that minimize or maximize solar intake (depending on the region), and insulation to prevent unwanted air flow between indoor and outdoor spaces.

However, energy efficiency gains are not just restricted to compensating for increased energy demand. Malta's smart grid solution (Goldstein, 2010) is an interesting example of electricity/water saving achieved by building a smart grid to govern both water and electricity. The grid will quickly pinpoint theft, leakage, and defective meters and will promote the efficient use of the resources through pricing options that will reward solar energy and conservation.

The transport sector provides another example. Here improvements in vehicle efficiency could compensate for the increased use of air conditioning. In Brazil, according to Schmitt et al. (2010), if incremental technologies (such as mass reduction, aerodynamic drag reduction, and rolling resistance coefficient reduction) are adopted by 2015, the reduction in sugarcane-planted area in 2030 will be 10 percent (since ethanol represents the most used fuel in light-duty vehicles in Brazil).

Energy storage technologies are a further option to shift electricity consumption away from peak hours. The main storage technologies are (Chen et al., 2009; Ibrahim et al., 2008): electrical energy storage (for example, capacitors and supercapacitors), mechanical energy storage (such as flywheels and compressed air energy storage systems), chemical energy storage (for instance, batteries), and thermal energy storage (for example, sensible heat systems such as steam or hot water accumulators).

Box 4.5. Fighting Drought Impact on Power Generation in Central Tanzania

Central Tanzania is critical in terms of hydropower generation, contributing 50 percent of Tanzania's hydropower production capacity. Some estimates reveal that although the energy reserve margin by 2030 could be as high as 26 percent with no climate change, it could fall to 12 percent under moderate climate change or 0 percent in a high-climate-change scenario. This low availability of hydropower might lead to significant additional costs for the country if it chooses to use thermal technologies, which are more expensive than hydropower. In the high-climate scenario the expected losses would lead to a 1.7 percent decrease in national gross domestic product (GDP) in 2030. Even in the moderate-climate scenario it would imply a 0.7 percent decrease in national GDP. However, efficiency provides a no-regrets option. The analysis mentioned above shows that it is possible to compensate most of the expected shortfalls in power production by implementing energy efficiency measures such as demand reduction and reduction of spillage at hydropower stations.

Source: ECA, 2009.

Decentralized Energy. As existing infrastructure ages there may be a new window of opportunity to build a more *decentralized energy structure*, based on locally available renewable energy sources situated in secure locations. This would reduce the probability of suffering large-scale outages when centralized power systems are compromised. This sort of regional, network-based system might also prove more flexible and adaptive, and therefore more able to cope with the increasing variability and unpredictability caused by environmental change.

Urban Design and Land-Use Planning. More than half of the world's population now lives in cities. According to UN estimates, the population living in urban areas is projected to pass from 3.49 billion in 2010 to 6.29 billion in 2050. This implies that cities are important and growing consumers of energy. Thus, urban policy and land-use planning will play an important role in improving the resilience of the energy system. In most cases this strategy will take place through demand-side management: building design (insulation, orientation), codes and standards (efficiency standards for appliances), and changes in consumption patterns (district heating/cooling, flexible working hours, and so forth). There is a wide range of examples of urban initiatives to reduce energy consumption and improve resilience (ETAP, 2006). But there are also supply-side opportunities to be exploited. The electricity industry (Acclimatise, 2009) recognizes that it will face major challenges in providing new generation capacity and supply reliability within urban areas and that in the future it will need to develop a new supply and demand system where consumers can also be suppliers with a variety of home generators.

Integrated Planning

> *While it may be true that preparing for climate change will call on resources that are useful for mitigation, it is just as likely that an open discussion about what is needed to prepare for the harmful effects of climate change will inspire action to reduce greenhouse gas pollution* (Snover et al., 2007).

Adaptation action may be required for an entire energy system or may involve interactions between different segments of the energy sector or other sectors, such as water or agriculture (Box 4.6). In fact, adaptation may involve not only different sectors, but also different agents (Chapter 4, "Adaptation Agents"). This happens because there are many indirect impacts of climate change in the energy sector, as well as indirect impacts on other economic sectors through impacts on energy.

Integrated planning within the energy sector and with others such as the water sector is therefore highly important (Haas et al., 2008). Energy and water systems are closely linked. The production/consumption of one resource cannot be achieved without making use of the other. And, climate change affects the supply of both resources. Therefore, policy makers cannot provide a good adaptation plan without integrating both sectors as parts of a single strategy.

Integrated assessment tools can be used to evaluate different adaptation options. The main advantage of an integrated assessment, as opposed to sector-specific analysis, is that it allows the indirect impacts of adopting a set of adaptation measures to be examined. Since there is competition for resources within the energy sector, as well as between the energy and other sectors, adapting to climate change impacts can have repercussions throughout the economy. Integrated resource planning and computable

Box 4.6. Regional Case Study: Climate and Energy Systems in the Nordic Countries (2007−2010)

The Nordic energy sector is sensitive to natural climate variability and change due to its reliance on electricity and energy production from renewable resources. The region launched a Climate and Energy Systems project in 2007 to look at climate impacts, and the development of the Nordic electricity system over the next 20 to 30 years. The project considers how the production of renewable energy in the Nordic area might change with global warming and focuses on energy security considerations and uncertainties. It seeks to:

- understand the natural variability and predictability of climate and renewable energy systems at different scales in space and time;
- assess risks resulting from changes in the probability and nature of extreme events;
- assess the risks and opportunities from changing renewable energy production;
- develop guiding principles for decisions under climate variability and change;
- develop adaptation strategies; and
- initiate a structured dialogue with stakeholders.

The project is due for completion in 2010 and could provide a useful framework and experience for other countries or regions facing similar concerns.

Source: Authors.

general equilibrium approaches are viable tools for assessing such issues. For example, in Lucena et al. (2010b), least-cost adaptation measures evaluated in an integrated approach led to a dislocation of natural gas from industrial segments to allow its use for power generation to offset the loss in hydropower system reliability (Box 4.7).

Box 4.7. Least-cost Adaptation Options for Brazil's Electric Power System

The Brazilian energy sector relies heavily on renewable energy sources. Some 45 percent of all energy produced in the country comes from renewable energy sources. In the power sector this reliance is even higher. Hydroelectric power plants accounted for 80 percent of Brazil's electric power generation in 2008 (MME, 2009). A set of climate impacts was projected for Brazil in Margulis et al. (2009). These impacts showed a decrease in hydropower generation reliability, as well as an increased demand for air conditioning and a decrease in natural gas power plant conversion efficiency.

Lucena et al. (2010b) used an integrated energy supply optimization model to simulate the least-cost adaptation options for the above-mentioned set of projected climate change impacts on the energy sector. By using the integrated energy planning framework MAED-MESSAGE (IAEA, 2006), they compared scenarios for the evolution of the Brazilian energy sector with and without the projected impacts.

Their results indicate that extra installed capacity that would have to be constructed by 2035 to prevent the system from failing due to the projected lack of reliability of hydroelectricity, as well as the other considered impacts. This installed capacity would be composed of natural-gas-fired power plants, higher-efficiency sugarcane-bagasse burning technologies (condensing extraction gas turbines), wind power, and nuclear or coal (depending on financial premises).

The integrated approach used in Lucena et al. (2010b) has the benefit of calculating least-cost adaptation options for a given set of climate change impacts and analyzing the indirect impacts on other energy-consuming sectors as well. For instance, the need for higher use of natural gas for electricity generation dislocated this fuel from other uses, such as industrial consumption.

Source: Authors.

When integrating climate risks into new investments, planners need to deal with the uncertainty related to climate scenarios; however, it may make sense to adjust now to expected long-term trends for which there is wide consensus, such as the anticipated increased in temperature and sea level rise. There is also a great deal of uncertainty about the evolution of technical and economic parameters used in the analysis that further adds to the already high level of uncertainty of climate impact assessments (see Chapters 5 and 6). The same applies for long-term decisions about energy access solutions. Incorporating possible impacts on long-term energy planning faces the same two problems: the rigid structure of energy infrastructure (long life span) and uncertainty about actual risks.

Usually, uncertainty is taken into account by using scenarios where the model assumes perfect foresight. In reality, however, decision makers do not have full information about the technical and economic characteristics of technologies and/or the constraints that the energy system will face in the future (Keppo and Strubegger, 2010).

Sustainable Biomass for Energy. To offset competition between energy and non-energy crops, it is important to invest in more efficient energy and fuel conversion techniques to improve energy availability. This means increasing crop productivity, increasing energy production per unit of biomass consumed, and assuring sufficient biomass supplies to convert into energy.

Crop management practices such as irrigation, mechanized harvesting, and development of new species through genetic improvements are good examples of practices that may work in favor of land productivity (Goldemberg et al., 2008). These would constitute adaptation actions by reducing the demand for agricultural land per unit of biomass produced. Ethanol production from lignocellulosic biomass, such as agricultural residues and woods that are largely available at low cost, can reduce impacts for the same reasons. However such technologies are still not commercially feasible at a large scale (Balat and Oz, 2008).

Pasture efficiency in Brazil is another interesting example. Pasture efficiency is currently very low (around one head of livestock per hectare), and improvements in livestock productivity can reduce areas needed for cattle, thus liberating land for agriculture. Pinto and Assad (2008) also suggest techniques such as rotating land use between pasture and crops with shorter periods of pasture (for example, for soybeans).

Generation and use of genotypes tolerant to higher temperatures, humidity, droughts, and pests may play a relevant role in increasing the yields of sugarcane, maize, soybeans, and other energy crops (Lucena et al., 2009b; Siqueira et al., 2001), especially if associated with irrigation. According to Persson et al. (2009), irrigation practices are the best way to minimize the negative effects of climate variability on the ethanol-maize supply in the United States. On the other hand, as irrigation becomes an important adaptation measure, water demand for agriculture may increase, causing other conflicts with energy and other economic sectors.

Integrating Energy and Water Resource Management. Globally, water demand is expected to grow due to increasing population and affluence. Climate change may have some effects on freshwater systems that can aggravate the impacts caused by other stresses, such as population growth, land use, and urbanization. Thus, current water management practices may not be able to deal with these impacts, particularly because of the traditional assumption that past hydrological experience provides a good guide to future conditions. This assumption may become untrue in a changing climate, demanding alternative water management practices and improvements in current ones (Bates et al., 2008).

From an energy perspective, competition for water can create stresses in a dryer climate due to the high water demand for power generation (mainly hydroelectricity, thermal power, and nuclear energy). The availability of water will have regional implications and directly affect the planning and siting of new capacity and the development of new technologies (Bull et al., 2007). Water resource management will therefore become an increasingly important tool for solving conflicts and optimizing the use of natural resources for energy and other uses. There is existing experience in this area, for instance, Amoco's oil refinery in Yorktown reduced its freshwater consumption by 14 percent and wastewater effluent flow by 24 percent by using optimization techniques (Tainsh and Rudman, 1999).

When it comes to thermal power plants, improvements in cooling system technologies are crucial for water management. Recirculating cooling systems are less vulnerable to modifications in water availability than once-through cooling systems, as the amount of water required in the former is smaller than in the latter (Feeley et al., 2008; Koch and Vögele, 2009). There is also the possibility of adopting air-cooled systems, which help in reducing evaporative losses of water or do not use water in the process[10] (Feeley et al., 2008).

Adaptation Agents

> *The Summer 2003 heat wave in western Europe affected settlements and economic services in a variety of ways. Economically, this extreme weather event created stress on health, water supplies, food storage and energy systems. In France, electricity became scarce, construction productivity fell, and the cold storage systems of 25-30 percent of all food-related establishments were found to be inadequate* (Létard et al., 2004).

Despite well-documented events such as the European heat wave of 2003, an extensive search has failed to reveal many active energy sector programs or projects in which adaptation *per se* is recognized as a major management issue in the energy sector. There is, however, increased evidence of adaptation actions being taken into account in other sectors, such as water supply and coastal management. Naturally, a prime focus within the context of climate change in most, if not all, energy projects is mitigation, but in many project documents the issue of "sustainability" is also raised, an issue that covers a wider framework than just adaptation to climate change. To address adaptation appropriately in the energy sector it is necessary to consider the perspectives of both the public and private sides, as recognized by the International Finance Corporation (IFC): *"The private sector is expected to finance most of the measures required to mitigate greenhouse gas emissions and adapt to the effects of climate change"* (IFC, 2010b).[11]

One difference in perspectives was acknowledged by IPCC Working Group II in the Third Assessment Report (TAR) of 2001, wherein "private adaptation" was defined as "*Adaptation that is initiated and implemented by individuals, households or private companies; private adaptation is usually in the actor's rational self-interest*" while "Public Adaptation" was described as "*Adaptation that is initiated and implemented by governments at all levels; public adaptation is usually directed at collective needs*." The rational self-interest of the private sector normally extends into public-private partnerships and other agreements, whereby the private side invariably will discount all costs and income streams, including grants, loans, and subsidies, to ensure financial self-interest across the contracted life of a project. Unless the commitment length of a project is sufficient to incorporate discounting of adaptation costs, and unless awareness of the adaptation issue is adequate, the danger exists that adaptation costs, often front-loaded for any infrastructure project, may be neglected by the private, and perhaps also the public, sector.[12]

Enabling government policies are undoubtedly a key aspect of ensuring effective public–private links, including attention to adaptation, in all countries. However IPCC Working Group III in the AR4[13] sounds a clear warning that, even with the best government policies, financial rewards will always remain the prime motivator for investments.

Role of Energy Regulators

Regulation helps manage the many positive and negative externalities facing the energy sector, including gains in productivity that are not perceived (or afforded) by the market, or local and global environmental impacts. Regulation can additionally support competition in transport networks and encourage risk management. Private economic agents (producers and consumers) benefit from energy security and reliability, but do not pay for them in the absence of regulation and/or economic incentives.

Global climate change may increase the need for regulation because:

- Climate impacts and risks to energy security are expected to increase in the long term.
- Climate change may reduce energy security and reliability, and lead to losses in external benefits and/or higher costs to maintain them.
- Decision uncertainty will rise with the higher frequency and intensity of extreme weather events.
- Private investors will be faced with increased uncertainty on long-term investments, which may reinforce shorter-term investment strategies due to the opportunity cost of capital.
- Climate policies that provide incentives for renewable energy generation and trading may impact energy transmission and market frameworks. For instance, increasing wind power generation in the energy mix may result in a large number of network connections and congestion within and across regions.

Energy regulators will need to improve resilience in an increasingly uncertain environment to manage possible losses in energy endowments, supply, and/or to meet higher energy demand. Regulators will also need appropriate climate information to support policy development. In the context of global climate change, regulatory action could include:

- Economic incentives and/or mandatory regulation[14] to increase investment in flexible energy supply facilities to ensure a quick response to supply-side losses linked to extreme weather events.
- Incentives for utility-led demand-side management programs; reducing peak demand can increase the power system's reserve margin.
- Rules for prioritizing energy cuts during extreme weather events.

- An auction system for consumers to allow them to bid for reductions in energy consumption during supply shortages.
- Research on advanced systems for electro-mechanical energy storage[15] to increase energy stocks and normalize supplies.
- Emergency biofuel stocks for supply interruptions during extreme weather events and to manage seasonal supply variations. Emergency stocks can be regarded as a public good, providing external benefits to private agents.
- Contingency plans and hedging mechanisms to support a system response to supply ruptures.
- Reduce information gaps. Energy system information should be regarded as a public good. For example, regulators could guarantee equal access to information for all economic agents so that climate change issues can be incorporated into decisions. They could develop mechanisms to finance the cost of obtaining and processing this information, either through direct financing or price taxes on energy tariffs. Energy utilities could also play a role, sharing relevant information on energy demand and supply projections.

The International Civil Aviation Authority provides an interesting sector example of an organization dependent on and continuously and effectively exchanging weather and climate information (Appendix I).

Summary Remarks

Although adaptation embraces no-regret actions that can be taken regardless of the realization of climate change scenarios, additional local and systemic or cross-sector adaptation measures will be essential to cope with increased uncertainty and other negative impacts of climate change on the energy sector. The adaptation options summarized in Table 4.2 can be compared with hotspots and impacts identified in Chapters 2 and 3 to help direct future research and improve resilience of a specific region's energy systems. In all cases, modeling and adaptation analysis should be conducted both in a sector-specific and in an integrated way, so as to account for the many complex inter-relationships within the energy sector and the whole economy. They will have to be tailored to the local context (Appendixes G and H). Finally, in a changing climate, risk management tools can help adapt to more uncertain planning and operational conditions. These are discussed further in Chapter 6.

Notes

1. This is the case, for example, of some renewable energy sources—such as hydropower and wind power—in which investment decisions have an intrinsic uncertainty related to climate conditions.
2. In the climate change context, external benefits in terms of mitigation can be an interesting option for adaptation policies.
3. Numerous personal communications during the author's visits to Panay.
4. International governance also plays an important role in building capacity for adaptation. Given that the most vulnerable countries are often among the poorest, international assistance for adaptation is critical. The international community has managed to create a range of funding streams to support adaptation in developing countries. The Global Environment Facility manages two separate adaptation focused Funds under the United Nations Framework Convention on Climate Change (UNFCCC): the Least Developed Countries Fund (LDCF) and the Special Climate Change Fund (SCCF), which mobilize funding specifically earmarked for activities related to adaptation.

The latter also covers technology transfer. The so-called "Adaptation Fund" has been recently established by the Parties to the Kyoto Protocol to finance concrete adaptation projects and programs in developing countries that are Parties to the Kyoto Protocol. The Fund is financed with the 2 percent of the Certified Emission Reductions issued for projects of the Clean Development Mechanism and flexible mechanisms. According to the World Development Report 2010 (World Bank, 2010a) current levels of finance for developing countries fall far short of estimated needs. Total climate finance for developing countries is US$10 billion a year today, compared with projected annual requirements by 2030 of US$30 to US$100 billion for adaptation.

5. Although adapting the operation and management of infrastructure can reduce vulnerability to climate impacts.

6. Thawing is likely to benefit some activities (for example, construction, transport, and agriculture) after it is completed, but the transitional period of decades or longer is likely to bring many disruptions and few benefits. Building infrastructure on permafrost zones can incur a significant cost because it requires that structures be stabilized in permanently frozen ground below the active layer, and that they limit their heat transfer to the ground, usually by elevating them on piles. For example, to prevent thawing of permafrost from the transport of heated oil in the Trans-Alaska pipeline, 400 miles of pipeline were elevated on thermosyphon piles (to keep the ground frozen), at an additional cost of US$800 million. The pipeline was completed at a cost of US$7 billion because of ice-rich permafrost along the route. This figure is eight times the estimated cost of installing the traditional in-ground pipeline (Parson et al., 2001).

7. Hallegatte (2006, 2008) casts some doubts on the optimality of such measures given the high level of uncertainty associated with forecasts of future climate conditions. She notes that according to some studies (Emanuel, 2005; Webster et al., 2005), the current high activity level in the North Atlantic arises from climate change, whereas others such as Landsea (2005) argue that it arises from multi-decadal variability. Thus, adopting land-use restriction measures in this case could result in unacceptable costs once scientific uncertainty is resolved. But, given that this scientific debate will take decades to be solved and waiting is not a good option, she suggests decisions should be based on scenario analysis and the most robust solution—that is, the most insensitive to future climate conditions should be chosen (Lempert and Collins, 2007).

8. The International Energy Agency's World Energy Outlook 2009 estimates that around US$550 billion needs to be invested in renewable energy and energy efficiency alone each year between now and 2030 if we are to limit concentration to 450 ppm CO_2 (IEA, 2009).

9. http://www.insurance4renewables.com/.

10. Direct dry recirculating systems do not use cooling water, while indirect cooling systems avoid evaporative losses of cooling water.

11. This quotation apples to all sectors, not just energy.

12. Many engineering projects remain based on the assumption of a stationary climate, using historical data for all planning.

13. p. 314.

14. For example, tariff incentives for power generators or concession rules for operating licenses for power generation.

15. Such as advanced batteries and ultra-capacitors or higher investments in heat pumps and/or pumped-storage hydroelectric facilities.

CHAPTER 5

Weather and Climate Information

Information forms the basis of any sectoral adaptation strategy. Two main information streams are required: the first is related to the workings of the energy sector itself and is not the focus here, but the second, all apposite weather and climate information, plus any further relevant environmental information, is. It is not just information on climate change *per se* that is required, but all information regarding management of the sector, such as recovery of fuels, site selection, transportation, generation, demand, and risk management. In practice the requirements are for historical information as well as for predictions on a range of time scales, plus specific information addressing processes such as environmental impact assessments. Basic details of hydro-meteorological and climate information streams, their accessibility, and the capacity to use these are outlined. A key section covers uncertainties in the data and in their uses.

Information Requirements for Decision Makers

Decision makers, whether energy providers or energy users, require information not necessarily on hydro-meteorological/climate parameters *per se* but on how those parameters affect all stages of energy production, distribution, and demand. Naturally, climate is only one factor in determining, say, demand, but it is a key factor. Future demand will depend on factors such as development policies, on entrepreneurship, on population growth, on changing consumer distributions and transport links, on poverty reduction, on improved efficiencies in energy use, and so on, as well as on future climate. Many of those factors are or will be themselves influenced by climate and climate change in ways independent of any immediate concerns of the energy sector. Satisfying future demands will require consideration of those factors, and more, of climate change, and of emissions mitigation policies and practices, perhaps as promulgated through any future international accords. At the same time, the energy sector will need to evaluate potential direct impacts of climate and future change on production and distribution, as discussed in Chapter 3, and will need to create strategies to address these to minimize possible adverse, and maximize achievable beneficial, consequences to meet future demand.

The information requirements of energy sector decision makers are not homogenous, either geographically, or geopolitically, nor are those of managers among energy users, all of whom may be concerned about the possible consequences of climate change for their energy resources, production, and demand. Geographical and political considerations may differ between countries, and between developed and developing countries, although all governments share a wish to attain and maintain national energy security and to boost supplies sufficiently to satisfy development. Within-sector information requirements differ between fossil fuel, nuclear, and renewable-source suppliers.

Table 5.1. Hydro-meteorological and/or Climate Information Requirements

From the perspective of mitigation versus adaptation—the former requires emissions-specific information, not least consequences of GHG concentrations for various emission policies, whereas the latter requires information that is related to resources, production, and demand.
From the perspective of understanding historical demand versus assessing future demand—the former is based on observations, the latter on predictions.
Similarly, from the perspective of assessing and interpreting climate sensitivities regarding past production and delivery versus assessing any changes in climate sensitivities for future production and delivery.
From the perspective of carbon-based generation versus nuclear generation versus generation through renewables—renewables mostly rely directly on climate, unlike carbon-based and nuclear generation, for which climate-sensitive infrastructure issues are prominent.
From the perspective of production in countries with substantial climate records available to assess pertinent climate sensitivities (predominantly northern developed countries) versus production in countries with limited climate records (predominantly southern developing countries).

Source: Generated by authors.

Energy users need to understand the background to their current demands, including any climate-driven factors, should those demands not be met or are threatened, and how all factors, not least climate change, will affect those demands, and their capacity to deliver in future. The entire matrix of information demand is complex and, to a certain extent, geographically, geopolitically, and sector specific.

There are several ways in which hydro-meteorological/climate information requirements in the energy sector might be categorized, as presented in Table 5.1.

For decision makers within the energy sector, nonexclusive hydro-meteorological/climate data needs include those listed in Table 5.2.

Further, there are a number of processes that might need to be undertaken for any energy sector facility, as presented in Table 5.3.

Table 5.2. Hydro-meteorological and/or Climate Data Needs

Location-specific information	Site-specific for raw material production
	Route-specific for raw material delivery
	Site-specific for energy production
	Route-specific for energy delivery
	Area-specific for demand assessment
Information with the required temporal resolution, with highest frequencies required, say, for wind, wave, and hydro generation	
Appropriate hydro-meteorological/climate parameters for each specific application	
Precision and accuracy of hydro-meteorological/climate information to within prescribed tolerances (however, as discussed in Chapter 5, "Uncertainty in Predictions," it may not be possible always for the information to meet those tolerances)	
Consistency between historical, current, and future hydro-meteorological/climate information to the extent possible between observations and predictions	
In some cases, hydro-meteorological/climate data in a form suitable for direct incorporation in energy sector simulation or prediction models, for example, for demand, pollution, or emissions modeling	
Access to and delivery of hydro-meteorological/climate information appropriate to requirements	

Source: Generated by authors.

Table 5.3. Climate Risk Management Tools

Climate Risk Assessment (CRA): an assessment of the vulnerabilities/risks posed to a project throughout its life cycle by weather and climate variability that might include:*	Impacts of adverse (or favorable) weather, such as storms and floods
	Impacts of adverse (or favorable) climate variability, including droughts
	Long-term impacts, beneficial and detrimental, associated with climate change
Climate Risk Management (CRM): proactive management of a project to mitigate the negative (and promote the positive) impacts of weather and climate variability and of climate change, based on a CRA and using all available information, including predictions on all time scales	
Climate Proofing: actions taken to lessen, or perhaps eliminate, the potential negative impacts through the life cycle of a project of weather and climate variability and of climate change based on a CRA and on CRM principles	
Pollution Modeling: an assessment and predictions of ground and atmospheric pollution emitted during the life cycle of a project	
Emissions Modeling: numerical calculation of the amount of greenhouse gases released through the life cycle of a project	
Environmental Impacts Assessment (EIA): an assessment of the impacts on the environment *in toto* of a project during its entire life cycle, including on the ground, on the scenery, on the atmosphere, on flora and fauna, and on society	

Source: Generated by authors.
Note: * The World Bank, and other organizations, refer to CRA and the planning of climate proofing together as "climate risk screening" or equivalent (World Bank, 2010c).

It is not possible to provide specific detail for all developing-world issues related to the lists previously presented, but notes on some of the more generic issues follow:

- There is often, but not always, a dearth of historical data in developing countries, resulting from numerous causes. For example: in the Central African Republic, most of the paper records held by the National Meteorological and Hydrological Service (NMHS) have been destroyed in a recent fire; in the Philippines, most NMHS records still reside on poorly stored inaccessible paper records, and several stations do not reach WMO standards. On the other hand, improvements in the networks can be noted in Colombia and Brazil and efforts are also under way to strengthen NMHS networks in Mexico. However, sometimes, no organizations other than the NMHS collect weather records in developing countries.
- Recovery of weather information to digitized, and therefore analyzable, records requires sufficient resources that often do not exist. Where data sources other than the NMHS exist, the records are often kept separate and not necessarily to WMO standards. Data access policies may exist in all cases.
- NMHS networks have focused traditionally on providing forecasts for the public, the government, and aviation. Often sector-specific forecasts are not provided. Rarely are the most advanced forecast systems, such as ensembles, considered. Resources to convert information to sectoral concerns, perhaps through modeling or EIAs, may be restricted.

Hydro-meteorological Parameters Relevant to Energy

The basic hydro-meteorological/climate parameters pertinent to the energy sector include those listed in Table 5.4.

Table 5.4. Hydro-meteorological and/or Climate Parameters and Select Energy Uses

Hydro-meteorological and/or climate parameter	Selected energy sector uses
Air temperature	Turbine production efficiency, air source generation potential and output, demand (cooling/heating), demand simulation/modeling, solar PV panel efficiency
Rainfall	Hydro-generation potential and efficiency, biomass production, demand, demand simulation/modeling
Wind speed and/or direction	Wind generation potential and efficiency, demand, demand simulation/modeling
Cloudiness	Solar generation potential, demand, demand simulation/modeling
Snowfall and ice accretion	Power line maintenance, demand, demand simulation/modeling
Humidity	Demand, demand simulation/modeling
Short-wave radiation	Solar generation potential and output, output modeling, demand, demand simulation/modeling
River flow	Hydro-generation and potential, hydro-generation modeling (including dam control), power station cooling water demands
Coastal wave height and frequency, and statistics	Wave generation potential and output, generation modeling, off-shore infrastructure protection and design
Sub-surface soil temperatures	Ground source generation potential and output
Flood statistics	Raw material production and delivery, infrastructure protection and design, cooling water demands
Drought statistics	Hydro-generation output, demand
Storm statistics (includes strong winds, heavy rain, hail, lightning)	Infrastructure protection and design, demand surges
Sea level	Offshore operations

Source: Generated by authors.

Numerous sources of these data are available for a range of time scales, both historical and as predicted for the future, as listed in Table 5.5.

Locations of global data received on one particular day in 2007 at European Centre for Medium-Range Weather Forecasts (ECMWF) (Reading, UK) are shown in Figure 5.1, which illustrates (clockwise from top left): surface, aircraft, orbiting satellites, stationary satellites. Data-sparse areas over the continents stand out as blank areas in the surface plot, over Africa in particular, and while data for these areas can be in-filled using information from the satellites, doing so creates a Catch-22 situation, as it cannot be done to high quality without using concurrent *in situ* data (Tribbia and Troccoli, 2008).

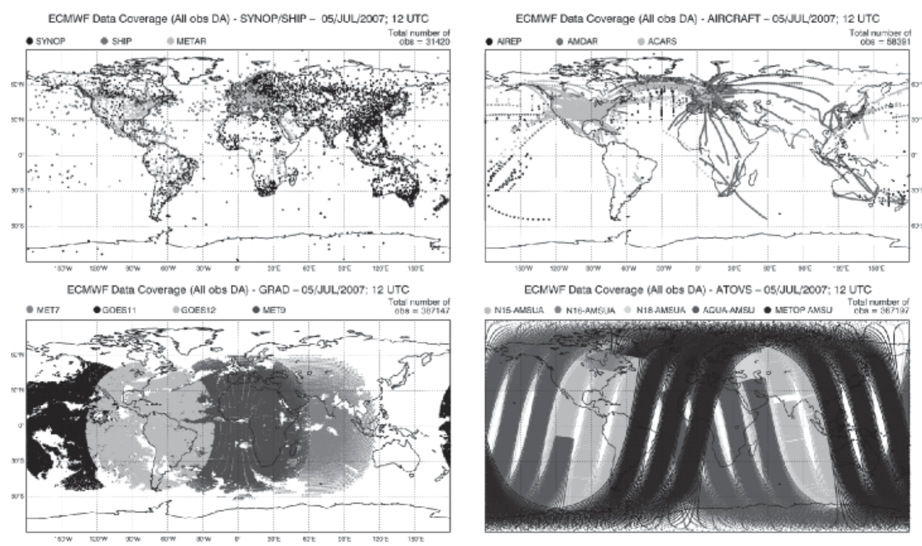
The forms in which hydro-meteorological/climate information is typically provided to the energy (and for that matter, most other) sector(s) are as presented in Table 5.6.

Table 5.5. Data Sources

Proxy data, such as from pollen and tree rings, for reconstructing historical climate—*developing world capacity in this field is low but the potential information source is rich*
Early records, such as missionary diaries, for recent historical climate reconstruction—*substantial records are locked in numerous documents and other paper archives, especially in developing countries—intensified data rescue and digitization is needed*
Surface networks (land and ocean) for *in situ* observations—*NMHS* networks are in decline in many countries and in many may not be to basic WMO standards; observations may be intermittent; data access may be difficult and subject to commercial restrictions; few supplementary observing networks exist in developing countries*
Upper air networks, including *in situ* wind measurements—*substantial decline in stations in the developing world, but only wind data is relevant to the energy sector*
Surface remote sensing, such as rainfall measurement radars—*few remote sensing facilities exist in the developing world, but they could be highly beneficial for the energy sector*
Mobile networks, such as on ships/aircraft and floating in the ocean—*for the energy sector, sea surface temperature, used in creating outlooks, and wave measurements are the most important*
Space remote sensing, frequently used to augment other networks to measure temperatures, winds, and so forth, especially over data-sparse areas—*potentially valuable to the energy sector but data quality is reduced in data-sparse areas since in situ observations are needed for calibration; limited resources exist in the developing world to receive and use space observations*

Source: Generated by authors.
Note: * Standard WMO terminology for National Meteorological and Hydrological Service; in some countries the two are separated, hence NMS and NHS.

Figure 5.1. ECMWF Data Coverage



Source: ECMWF, 2009.

Table 5.6. Hydro-meteorological and/or Climate Typically Provided to the Energy Sector

Time series based on observations at a point
Spatially and/or temporally averaged time series—numerous time series exist that have been created to assist in assessments of climate across all or parts of the globe in a consistent manner, including over data-sparse regions; they are formed using statistical methods and all available observations, and typically are monthly or seasonal averages over 2.5° or 5° latitude/longitude (the quality depends on access to in situ measurements and so declines over many developing countries) (See for instance Climate Research Unit, 2010); ongoing projects such as ACRE[a] have the aim of improving these time series.
Re-analyses—these have been created for several decades using advanced modeling techniques and observational archives (Appendix B), and are presented on grids varying between about 0.5° and 2.5°; in many respects these are the best historical data available for data-sparse regions, but inevitably degrade in quality over data-sparse regions (developing countries may have limited capacity to manipulate and interpret re-analysis data) (ECMWF, 2008; JMA, 2008; NOOA, 2010c; NASA, 2010).
Forecasts to ~15 days—in principle these should be available in all developing countries but retain skill for fewer days at lower latitudes (developing countries may have limited capacity to post-process and interpret forecasts according to specific customer needs, as well as to provide rapid information delivery to users).[b]
Outlooks beyond ~15 days to a year (or two), normally presented as monthly or seasonal averages across areas of perhaps 200−300 km^2 (despite much development in several parts of the developing world, where highest forecast skill exists as a result of the nature of climate variability, not least for seasonal forecasts in Africa,[c] the ability to produce, interpret, and deliver outlooks to the specific interests of users remains limited).
Decadal projections would be beneficial for infrastructure investment decisions but despite extensive and ongoing research are not yet advanced to a usable stage (Walker Institute, 2007).
Climate projections, in general as assessed by the IPCC (because of insufficient resources many developing countries have had relatively limited input to the IPCC climate projections).
Climate impact projections are normally based on IPCC climate projections, often by running, say, a crop model using climate model outputs (limited resources in the developing world to undertake the analyses).

Source: Generated by authors.
Note: a. http://www.met-acre.org/.
b. It is important to read Chapter 5, "Uncertainty in Predictions," on uncertainties in conjunction with this and following forecasts.
c. For the latest Regional Climate Outlook Forum (RCOF) predictions, see http://www.wmo.int/pages/prog/wcp/wcasp/clips/outlooks/climate_forecasts.html.

Information Limitations and Impediments

There are three important impediments/limitations in the use of hydro-meteorological/climate information in any energy adaptation activity: access to observations and access to predictions, and uncertainty in predictions.

Access to Observations

Access to observations is a complex issue, although a reasonably detailed outline has been provided by Harrison and Troccoli (2009). The United States is prominent as one of the few countries today that offers basic hydro-meteorological/climate information at no, or only a handling, cost. Many other countries, including most in the developing world, have progressively followed Europe's lead in the 1990s of commercializing and seeking cost recovery for meteorological services. Internationally agreed rules for commercialization/cost recovery of data from NMHSs are formulated under WMO Resolution 25 (hydrological data) and Resolution 40 (WMO, 2010) (meteorological data). Briefly, these Resolutions categorize data as those that are:

- **Essential to support WMO international operational programs.** Data under this category are freely available for only a handling charge, but these data in general are unlikely to be sufficient to support the observational needs of the energy sector.
- **Support other WMO programs.** Data under this second category may be available at a handling charge for research purposes but at a commercial rate for other purposes; there may be value in these data for the energy sector.
- **The remainder.** Each country has autonomy over policy for this last category, which often includes rainfall data from voluntary observers that would be of benefit to the energy sector.

Guidelines exist, but in practice countries retain substantial sovereignty over which data fall under which category, what charges are made, and how national policy is enacted. Non-NMHS data providers may enact freely their own data policies. Numerous issues of data quality, archiving, and access exist, for both NMHS[1] and other observations, but these issues vary by country.

Access to Predictions

Access by NMHS centers to weather predictions up to about 15 days in advance is fairly straightforward, although the precise situation varies by recipient country. In principle all WMO Member State NMHSs should have rapid access to short-range forecasts. Various sources of predications are also available on monthly and inter-annual time scales (Appendix J). In general, access to these predictions from WMO-linked centers is available either gratis or through agreement, while access to those from research centers and universities is often made available freely through the web.

Climate Change Projections—Modeling and research centers, including universities, around the world produce th climate change projections that are collated by the IPCC in reports produced every few years, the latest being the AR4 published in 2007. The AR4 from IPCC Working Group III, which deals with mitigation of climate change in the sense of reduction of emissions, includes a half-page section (numbered 4.5.5) that mentions adaptation within the energy sector, most specifically from the perspective of increased vulnerability under a changing climate (IPCC, 2007c). Similarly the report of IPCC Working Group II summarizes impacts of climate change on demand and production (numbered 7.4.2.1), while Chapter 18 covers interrelationships between adaptation and mitigation, but mainly from a policy perspective. Some regional information is provided, such as for Australia and New Zealand in 11.4.10, Europe in 12.4.8, and North America in 14.2.8, but it is noteworthy that the AR4 overall provides minimal information on adaptation in the energy sector in developing countries (IPCC, 2007b).

Models used for climate projections tend to employ relatively large grid sizes, of perhaps 2° latitude/longitude, resolutions often considered too coarse for decision making. Projections may be downscaled to smaller resolutions either by statistical techniques or using regional climate models (RCMs). RCMs have been used for downscaling projections in a number of developing countries, in particular using the UK Met Office's PRECIS Model (PRECIS, 2010). Few statistical downscaling studies have been made in developing countries, although this approach is readily accessible provided there are adequate historical data.

Uncertainty in Predictions

The science behind prediction uncertainty is too complex to cover here, and only consequences will be discussed. The optimum manner of addressing uncertainties in predictions is to use ensembles from numerical models (uncertainties can also be estimated for statistical models); the outcome might be an ensemble of perhaps 51 different predictions[2] for a specific period, none likely to be "correct" in all regards, and none of which can be selected *a priori* as the "best" prediction, but that together can be used to produce a probability distribution of likely outcomes. Decision making given probability distributions may be more complex than a single deterministic prediction, but ultimately provides outcomes that take into consideration the entire range of potential futures rather than single, possibly erroneous, ones.

Ensembles are available for predictions on all time scales. For example, IPCC projections are built from ensembles created using a number of models (23 in the AR4). An additional complexity is introduced within climate prediction in that the major drivers of change, atmospheric greenhouse gas concentrations, are unknowable into the future and need to be treated through scenarios (the SRES Scenarios). Forty SRES Scenarios have been produced but only three or four have been examined in detail with the models (Appendix A). However, it should be noted that downscaled projections, say, as produced using PRECIS,[3] normally are not run as an ensemble and therefore may not include information on uncertainties.[4]

A key to understanding the limitations and uses of predictions is provided by forecast verification.[5] There are numerous ways to verify deterministic and probabilistic forecasts, but these are often drawn from the statistical perspective of the forecaster and are difficult to interpret in terms of the needs of the user. Verification in developing countries is often weak and not undertaken in general to satisfy the concerns of any particular sector.

Uncertainties do not affect predictions alone; they may also be a factor in, say, the interpretation of historic data, and not necessarily just those from hydro-meteorological/climate sources. For example, trends are often discussed in the context of climate change, but the rate of these, or even the direction, can be highly sensitive to the analysis period, particularly for irregular parameters such as rainfall. The fact that a trend has existed in the recent past is no certain guarantee of its continuation into the future. Taking this point further, temperature trends as assessed by the IPCC are likely to continue upwards for many years unless there are substantial international actions regarding emissions mitigation; however, there is uncertainty in the rate of warming as assessed by an ensemble of models. The impression may be gained from the AR4 that future rainfall trends are also unidirectional at each location, but this may not be the case, and rainfall trends may readily reverse or disappear over periods of a few decades.

Management of uncertainties may take various forms. For example, by calculating cost/loss profiles for each decision option, through economic analysis to identify the most advantageous decision, and by establishing contingencies in the event of an erroneous decision. In addition to direct actions to manage uncertainties, there are approaches that facilitate the environment in which decisions under uncertainty are made (Table 5.7).

Table 5.7. Methods to Facilitate Decisions under Uncertainty

Insurance (weather-index-based insurance as used for agriculture might be used in the energy sector, say, for insuring renewable generation facilities) (Chapter 4, Box 4.4)
Climate risk management (CRM) and *climate proofing* (Chapter 6)
Education is perhaps the most powerful tool to be used in managing uncertainties; stakeholders knowledgeable in the causes and management of uncertainty are far more likely to take appropriate actions than others not so well versed*

Source: Generated by authors.
Note: * According to a recent report by the BBC World Service Trust and the British Council, Africans in 10 countries felt they knew little about climate change, its causes and consequences; it is not unreasonable to doubt the aversion of such people to embrace actions necessary within the context of climate change (BBC, 2010).

Interpreting Information: Tools and Process Gaps

Objective approaches to interpreting information, and to predicting events, can be divided simply into two major categories, referred to in the following as numerical and empirical approaches. Weather and climate models fall into the numerical category, as do many models used in the energy sector to simulate, say, the behavior of a dam or the performance of wind turbines. Empirical approaches are based on observed data for the system and provide simulations in a statistical sense. Insufficient attention is often given in decision making to inherent uncertainties, whether numerically or empirically based.

An examination has been made of available numerical and empirical approaches and the associated uncertainties and process gaps associated with demand prediction. Process gaps are defined as both information gaps and gaps in the capacity to convert information to decisions. Demand prediction spans periods of the next few days to the next few weeks and the next few decades. In all cases the following discussion centers on information to support pertinent decisions on using carbon-based fuels, nuclear fuels, and a range of renewable sources. Information challenges are summarized in Table 5.8 and are specifically focused toward developing countries. Aspects already covered in relationship to information, its availability and uncertainties, and the use and interpretation of hydro-meteorological/climate predictions are not repeated in the table. As appropriate, the information covers exploration, source mining, delivery to the generation site, generation, and energy delivery.

Capacity to Use Weather and Climate Information

Especially in the developed world and mainly in large corporations, weather and climate is regularly factored into energy planning and operations. Electricité De France (EDF), for example, is a major energy company with a diversified fleet of production assets that include thermal (nuclear, coal, fuel, and gas) power generation plants, renewable energy sources (mainly hydropower), and a rising number of wind, biomass, geothermal, and solar production units. EDF directly employs weather/climate specialists to ensure that decisions about maintenance scheduling, networking, inventory and stock management, demand forecasting, forecasts of production from renewables, and other

Table 5.8. Information Challenges

Demand	
Empirical approaches linking demand to weather and to calculate demand based on weather/climate predictions on all time scales	On longer time scales empirical approaches will need to extrapolate current demand projections to include increased demand through economic and population growth and to consider national development policy issues (such as the Millennium Development Goals, poverty reduction strategies, and National Adaptation Plans of Action). National capacity may be stretched to provide expertise in all areas; but often the priority in developing countries is to increase energy generation for development rather than to link supply to demand and related weather/climate considerations.
Coal-, oil-, and gas-fired generation	
Numerical approaches include site forecasts for operations, pollution modeling, offshore wave forecasts, scenarios for climate proofing, and emissions modeling; empirical approaches include site CRAs and EIAs and climate proofing	Notwithstanding all uncertainties, capacity to assess local climates, to provide CRAs and EIAs, to produce site-specific predictions on all time scales, and to undertake pollution and emissions modeling may be limited, and CRM skills may be limited.
Nuclear generation—as per carbon-based generation	
Ground water (with meteorological) modeling for radiation releases in emergencies, scenarios for climate proofing and for site decommissioning	Capacity to handle radiation releases may be an issue, as may ground water data and modeling. CRM skills may be limited.
Hydropower generation	
Hydrological modeling, including dam simulation modeling; empirical evaluation of river flows, flood and drought statistics, and climate change impacts; CRAs, EIAs, and climate proofing	Hydrological data and modeling may be an issue; real-time rainfall monitoring, including remote rainfall estimation (radar/satellite), may not exist; CRM skills may be limited.
Solar generation	
Empirical evaluation of radiation (need not be at site but within the same climate regime) and of change, plus of damaging weather, including hail; CRAs, EIAs, and climate proofing	Future changes in radiation at a point are not often considered but can be assessed; CRM skills may be limited; hail records are unlikely to be detailed even if they exist.
Wind generation	
Local-scale wind modeling, including modeling of wind power density and local wind (and wave and sea level rise if offshore) predictions; CRAs, EIAs, and climate proofing	Specialized meso-/microscale models are available that might be used in developing countries; wind records, where they are available, are often at 10 m even if they are pertinent to a generating site but generators require records at ~75m; CRM skills may be limited; hail is an issue as per solar generation.
Ground source and geothermal generation	
Though these techniques are logical to include, generation is climate related only to a limited extent and the main issues are climate proofing of site and supplies	
Biomass and biofuel generation	
Pollution and emissions modeling, crop growth management, including crop modeling; CRAs, EIAs, and climate proofing	Issues with crop modeling skills and CRM.
Wave generation	
Wave modeling and statistical evaluation of waves, estimation of climate change, including sea level rise, effects on waves, plus storm statistics and future change, and wind forecasts; CRAs, EIAs, and climate proofing	Wave data may be insufficient, and the capability to provide offshore forecasts and wave modeling may be limited. Requires specific expertise to assess climate change aspects; CRM skills may be limited.
Tidal generation	
Wave and tidal modeling and of tidal power density, short-range storm predictions; CRAs, EIAs, and climate proofing	Tidal power density may be difficult to estimate given data and resources, limited ability to provide site specific predictions and CRM

Source: Generated by authors.

factors incorporate weather/climate information (Dubus, 2010). Similarly, insurance and finance companies with an interest in energy also count meteorologists/climatologists in their ranks (for example, Mailier, 2010).

Despite this close engagement, the complexity of the Earth's system is such that impacts from some weather- or climate-related events require an even higher level of attention. The marked increase in the wholesale gas prices in the United Kingdom and other European countries during the winter of 2005–2006 was caused by a cold wave over much of Europe and compounded by geo-political factors (Troccoli, 2010b). The disruptions caused by Hurricane Katrina in 2005 (as well as by other hurricanes) to oil and gas operations in the Gulf of Mexico (Froude and Gurney, 2010) provide another example.

The level of engagement in developing countries differs significantly. With the exception of major organizations, such as VNIIGAZ Ltd, Russia (Vlasova and Rakitina 2010), that receive dedicated information, major energy operations either receive climate risk management input from northern institutions or none is applied.

The system developed by Météo-France to predict flow in the Senegal River that is used in the management of the Manantali Dam (Mali) is an example of good practice. The Manantali Dam was built in 1987, and supplies 800 GWh/year of power. It also controls about 50 percent of downstream flow, in an area where recessional agriculture (flooding, followed by planting) is practiced. The rainy season is from June to October, recessional agriculture begins in November, and there is no rain from November until May. The challenge is to maintain electricity production throughout the year while allowing downstream flooding during the period of peak flow. At the same time, river heights need to be maintained for navigation, irrigation support, and flood management (Patt and Winkler, 2007). The flow prediction system has optimized hydropower generation and guaranteed that artificial flooding for flood recession farming can be achieved in three out of four years (compared to once in five years if no forecast information is used) (Julie and Céron, 2007).

Notes

1. WMO standards exist for NMHS data but may not be applied necessarily to other data.
2. There are a number of ways of producing ensembles, but the basic principle is to test the sensitivity of a prediction to small but realistic changes in the manner that prediction is produced, two of the most common approaches being to use slightly different starting points for each ensemble member or different models.
3. Downscaled projections from a model such as PRECIS (others exist) are popular as they provide detail at a scale of, say, 50 km, much finer than the 200–300 km typical of the global models. However that detail depends on the quality of the projections made by the companion global climate model (normally one of the Hadley models with PRECIS), and the need to run ensembles is just as critical as with the global models.
4. A new international program, CORDEX, is expected to produce ensembles of downscaled climate change scenarios using RCMs in time for the IPCC AR5.
5. Verification is a statistical evaluation of how well a set forecasts performed when measured against observations.

CHAPTER 6

Climate Resilience

Not only is the energy sector at risk from climate change *per se*, together with any amendments to demand that climate change might bring, but it is also at risk from current hydro-meteorological/climate variability. Risks handled today, while perhaps not sufficient to address climate change in full, are likely to help address risks into the future. These risks cover all areas concerning the energy sector, including demand, exploration, site selection, infrastructure development, operations, maintenance, and delivery. They originate across all energy sector contexts from almost every aspect of hydrology, weather, and climate, and, as experience has indicated, the risks are sufficiently great to threaten supplies, with all implied downstream impacts on society, commerce, and development. This chapter discusses risk management from an adaptation perspective, focusing on the consequences of climate change, including increased variability.

To increase climate resiliency, climate change adaptation needs to be integrated into energy planning and decision-making processes at all relevant levels. Equally, energy sector responses to climate change need to be considered in the broader development context. The fundamentals of risk management are already widely appreciated and practiced within the energy sector. The basic process involves: risk identification, an assessment of vulnerability to each risk, prioritizing actual risks for operations (effectively, risk versus vulnerability), and identifying and implementing actions to eliminate or minimize risk. This generic approach is applied as a normal part of engineering and other operations in the energy sector. Nevertheless, climate, including climate change, does not appear to have been considered as a major risk for existing infrastructure or future plants. Climate mitigation has been scrutinized extensively by the energy sector, but adaptation to a far lesser extent. Even the strategy of the international 3C Consortium[1] of energy generators covers only mitigation, technology transfer, and adaptation support for the developing world, but not adaptation within the energy sector *per se* (Combat Climate Change, 2010).

And it is not just the developing world where energy adaptation is required: "*The water shortage across eastern Australia is now so acute it has begun to affect power supplies, and the country is at risk of electricity shortages next year. 'I think we are in denial, and are going to have brownouts in NSW if we don't get snow this winter,' a source within the electricity market said.*" (The Age, 2007.) Threats to power supplies from rainfall shortages are a worldwide concern: "*Climate change is expected to bring less precipitation and more extreme droughts to certain parts of the world, causing electricity shortages in hydro-reliant countries*" (Circle of Blue Waternews, 2010). But lack of water is not the only adaptation issue, as illustrated in England in 2007: "*Flood Chaos: Two Inches from Disaster—Flood levels have peaked just two inches short of the height which would have swamped a major power station—leaving 500,000 homes without electricity*" (Sky News HD, 2007).

In addition to issues of limited awareness within the sector, there is a need for research and practical tools to address all aspects of risk management under climate uncertainties. The International Finance Corporation (IFC) summarizes the risk issue for private concerns in a manner that is also relevant for the public sector: "*Climate change poses a series of risks to all private sector companies … yet a question still remains—how to measure that risk? This is a question the private sector has not addressed yet, lacking so far baseline information, methodology and strategy. This may pose significant challenges, in particular in developing countries where the impacts are expected to be the most significant. Methodologies for assessing some of these risks exist, but not with data and tools tailored to the needs of private sector investors and government decision makers*" (IFC, 2010a).

Climate risk assessment (CRA) and climate risk management (CRM)[2] can provide an integrated framework to guide decisions and actions. These generic terms are used from the climate side to cover the entire chain of actions, but both are immature processes that receive far less research attention and funding than climate change science itself, and both have been examined mostly in areas such as health (for example, malaria) and agriculture (for example, crop growth). Lessons learned undoubtedly could be transferred to the energy sector, although at best that might provide only an initial impetus.

Further, the information base from which energy risks need to be assessed and managed is far from perfect. From the hydro-meteorology/climate perspective only, not only does much of the necessary information base not exist (see Chapter 5), or if it does exist it is difficult to access, but all predictions carry uncertainties of magnitudes sufficient to compromise decisions, whether short-range predictions for operational maintenance and supply decisions, longer-range predictions for operational scheduling and supply risk management, or climate change projections for informing about impacts on energy supplies that will affect development. These uncertainties sit alongside others such as future demand, development requirements, and government policy.

A warning also needs to be sounded regarding the use of single-scenario assessments of risk. There are examples in the literature of modeling approaches to examine energy sector risks relevant to climate change in which a single model and/or single scenario has been used. There is nothing incorrect in strict scientific terms in the results produced by this approach, but it should always be borne in mind that single-realization approaches do not reveal the true extent of the uncertainties involved.

With this in mind, there are probably two basic approaches to next steps. The first is effectively the "do nothing" approach, to permit complacency, or perhaps more appropriately lack of awareness, to dominate, to allow the focus to remain on mitigation, to plan along traditional lines, perhaps taking climate risks into account as they become apparent, and to manage any issues retroactively. The second is the proactive approach to mainstream risk management.

This chapter explores the desirable outcomes of adaptation decisions and strategies, and the main gaps and options for integrating climate risk considerations into energy systems. It recognizes the various levels at which integration needs to take place and the multitude of stakeholders involved.

Awareness versus Knowledge

Climate change is expected to have a wide range of direct and indirect effects on energy production and consumption patterns. Though research and policy-oriented literature on energy-related climate risks, impacts, and their management is emerging, it is still generally scarce. This is particularly striking given the research efforts directed at climate change mitigation (Mideksa and Kallbekken, 2010; Wilbanks et al., 2008). There is also considerable variation in the geographical and system coverage of available literature. For example, climate information on cooling and heating demand and on hydropower and wind energy is more widely available than that for thermal power, solar power, biomass energy, and electricity transmission and distribution systems. Literature is scarcer for middle-income countries and low-income countries.

Detailed information on possible climate effects is needed to make decisions about short-term adaptive management and longer-term planning, related to, for example, technological change (Wilbanks et al., 2008). It is also important to raise awareness and concern at a project, policy, and planning level about climate impacts on energy services and the wider implications for development. The literature supports identification of key issues and potential adaptation options but the knowledge base is relatively limited for making generalized conclusions on the integration of adaptation options in planning and decision making. There are only limited examples of sector, regional, and national climate risk management and planning efforts and very few systematic efforts on the ground–the recently launched ESMAP pilot program being a notable exception (World Bank 2009e, also Appendix L).

However, the growing literature on the subject illustrates increasing scientific awareness. Recent mass media coverage of disruptions to energy supply or increases in energy and fuel prices caused by extreme weather events (heat waves in Europe in 2006, Hurricane Katrina, and so forth) has sparked public interest (Puppim de Oliviera, 2009). Government papers increasingly refer to energy sector climate vulnerability, as do studies by development agencies and the agendas of international meetings. However, energy sector climate resilience is rarely assessed in detail at the policy level, illustrating that integration of energy sector adaptation options and actions is yet to take place.

Decision Making under Uncertainty

> *Responding to climate change involves an iterative risk management process that includes both mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity and attitudes to risk. Risk management techniques can explicitly accommodate sectoral, regional and temporal diversity, but their application requires information about not only impacts resulting from the most likely climate scenarios, but also impacts arising from lower-probability but higher-consequence events and the consequences of proposed policies and measures* (IPCC, 2007d, p. 64).

A risk-based approach to climate change adaptation can support informed decisions to avoid maladaptation and minimize the risks of over- and under-adaptation. This section describes risk management approaches that are being used to identify adaptive responses and increase the climate resilience of energy systems. It highlights areas where efforts should be strengthened or knowledge gaps exist.

Climate Risk Management

Risk assessment and management are already important aspects of energy decision making. Energy providers are accustomed to policy changes, shifting global market conditions, changes in financial variables such as interest rates for capital infrastructure lending, and climate variability (Wilbanks et al., 2008). Energy users cope with price fluctuations as well as near-term shortages in energy availability, caused by extreme weather events, damages to energy distribution infrastructure, and negative impacts on hydropower supply. In many developing countries users face risk and uncertainty due to the widespread unreliability of energy supplies or a lack of access to modern energy sources that requires frequent decisions about weather-impacted fuels (typically woodfuel, charcoal, kerosene, liquefied petroleum gas [LPG], and electricity).

Climate considerations are especially apparent in planning and investment strategies for renewable energy, resources that depend directly upon climate parameters. But at least in some countries, electric utilities routinely consider weather variables when developing strategies (Niemeyer, 2005). Ram's (2009) analysis of an integrated risk framework for gigawatt-scale deployments of wind energy in the United States recognizes underlying uncertainties in the renewable energy sector and stresses the need for life cycle or energy system risk assessments across all energy supply options to make clear decisions for designing the future national energy systems.

Figure 6.1 illustrates a risk-based framework for adaptation decision making developed by the UK Climate Impacts Program, UKCIP (Willows and Connell, 2003). It illustrates the cyclical nature and iterative risk management process that uses uncertain long-term impacts to develop short-term adaptation priorities and options. This is useful for two main reasons. First, it provides the short-term policy or project analysis and advice that decision makers need. Second, new information and data can be incorporated continuously as they become available to alleviate constraints on decision making posed by uncertainty. Decision-making criteria can be revisited when new information on costs and feasibility becomes available.

Climate risk management requires an interdisciplinary effort where the tools and knowledge of scientists, energy analysts, and economists, policy makers and planners, and citizens are combined. Participatory approaches and tools are essential for increasing the climate resiliency of energy systems in a manner that is most beneficial to society.

Appendix K provides other examples of climate risk management frameworks. Collectively, this experience highlights at least four features that are relevant for the energy sector:

- **Practicality**: Combining the probabilities and consequences of climate impacts allows a comparative assessment of the importance of low-probability/high-consequence events with more frequent events with less severe consequences (Willows and Connell, 2003).
- **Flexibility**: The framework can be applied to current and expected future conditions, to diverse locations, to different types of climate risks, to economic impacts, and to decision making at various levels independently or through integrated risk management (ADB, 2005; IGCI, 2010; OECD, 2009; Willows and Connell, 2003; ECA, 2009).
- **Compatibility**: The framework builds on established and widely used tools and techniques for quantitative and qualitative risk assessment, economic appraisal, and environmental assessments (ADB, 2005; Willows and Connell, 2003; ECA, 2009).
- **Stakeholder Engagement**: The framework facilitates information sharing, coordination, and cooperation among relevant stakeholders (ADB, 2005).

Dealing with Uncertainty

The energy system–climate impact relationship is highly complex and uncertain. Uncertainty arises when estimating the future growth (negative or positive) in greenhouse gas emissions and their concentration in the atmosphere, as well as the extent of warming. Uncertainty increases when regional climatic responses are taken into account, and further still when considering impacts on various human and natural systems. At a project level, planners and decision makers need local, specific, and detailed information, raising uncertainty. This "cascade of uncertainties" (IPCC, 2001a) means the range of outcomes can be considerable (Box 6.2). A risk-based framework can help planners and decision makers identify the most important risk factors and describe the uncertainty associated with each (Box 6.1).

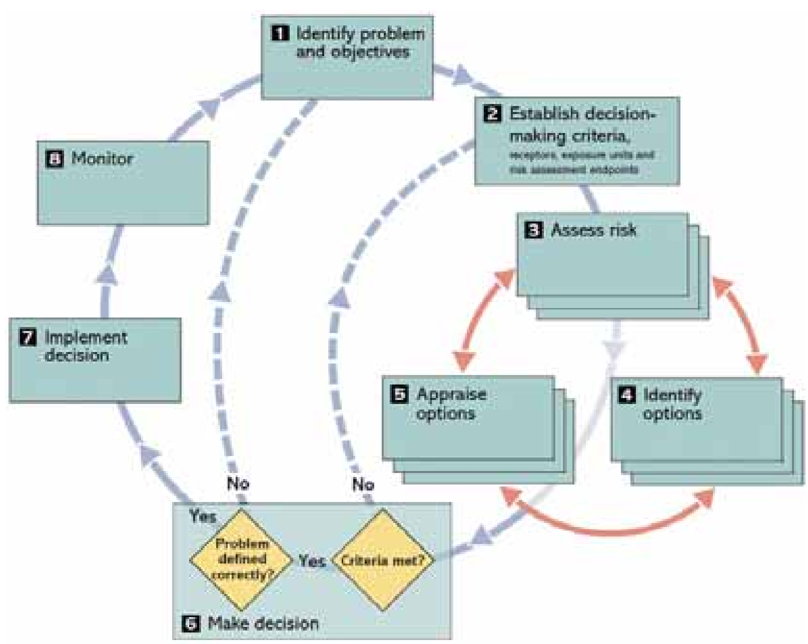
Box 6.1. Definitions of Risk and Uncertainty

Risk is the probability of an event and its magnitude. Risk considers the frequency or likelihood of certain states or events (often termed "hazards") and the likely consequences for those exposed to the hazardous event.

Uncertainty exists where there is a lack of knowledge concerning outcomes. It may result from an imprecise knowledge of the risk. However, even when there is a precise knowledge of frequency and magnitude of the event there is uncertainty because outcomes are determined probabilistically.

Source: Willows and Connell, 2003, Box 1.1.

Figure 6.1. The UKCIP Framework for Climate Change Adaptation Decision Making under Uncertainty



Source: Willows and Connell, 2003.

Box 6.2. Types of Uncertainty

"Real-world" uncertainty stems from events that can only be described probabilistically. To illustrate, while it may be possible to estimate the probability and magnitude of floods and droughts within a specific period of time, it is not possible to determine their exact timing (day, month, and year) and location. Uncertainty also arises from natural variability—for example, from environmental events (partial collapse of ice sheets, volcanic eruptions, earthquakes, and so forth), social and financial (for example, stock markets) systems, and future choices made by businesses, societies, or individuals.

Data uncertainty arises from measurement error (random and systematic, such as bias), incomplete or insufficient data (limited temporal and spatial resolution), and extrapolation (based on uncertain data).

Knowledge uncertainty occurs when there is a lack of useful data on the processes, interactions, and dependencies of different parts of a system, or the probabilities of possible outcomes. It includes uncertainty about future economic, social, and ecological systems. Scenarios can capture aspects of uncertainty about the future.

Model uncertainty may arise from model choice and structure, model input variables, model parameters, and model output variables and values. The consequences can be assessed using uncertainty and sensitivity analysis.

Outcome uncertainty concerns uncertainties in the environmental, economic, and social impacts or outcomes for climate change and socioeconomic scenarios or decision options.

Decision uncertainty is the rational doubt regarding which decision to adopt. It is partly a product of outcome uncertainty and uncertainty about the future, but may also arise from conflicting social and economic value systems that may govern the choice between options and introduce uncertainty in the ranking of identified adaptation options.

Source: Based on Willows and Connell, 2003.

Two Types of Decisions: Climate Based and Climate Influenced

It is useful to distinguish between two broad types of climate-sensitive decisions. First, some decisions are based on a recognized need to manage current climate variability and extremes and/or to address adaptation in anticipation of longer-term climate change. Decisions on renewable energy sources where climate variability and extremes are important for management decisions are specific examples. In this case, awareness and knowledge is high.

Second, climate variability and change may be one of many uncertainties that influence the outcome of a decision. Examples include decisions about where to locate thermal power plants, demand-side management and energy security strategies, or in broader development areas, such as urban and coastal planning and water resource management. In this case, raising awareness among planners and decision makers may be an important first step to ensure that due attention is paid to the potential impacts of climate change. Awareness and knowledge of potential climate impacts and the degree of exposure to these impacts will influence a decision maker's attitude and the weight the decision maker attaches to climate risk management.

Three Types of Adaptation Error

An inherent risk of adaptation decisions given the underlying uncertainty is that they may turn out to be mistaken or less than optimal. Building on Willows and Connell (2003), we distinguish between three types of adaptation decision errors:

- **Under-adaptation,** where too little emphasis is placed on climate risks, and opportunities for climate adaption may not be given sufficient priority. It may result from a failure by the decision maker to consider or identify climate change or specific climate variables as important when making the decision, or in cases where nonclimate factors have been given too much weight compared to climate factors.
- **Over-adaptation,** where climate change or related variables are overemphasized and in practice turn out not to be significant, or too little weight has been given to nonclimate factors compared to climate factors. Over-adaptation may be a deliberate strategy of a (risk-averse) decision maker, adopted as a precautionary approach in the face of risks of irreversible or serious climate change damage.
- **Maladaptation,** or actions taken that (unintentionally) constrain the options or ability of other decision makers now or in the future to manage the impacts of climate change, thereby resulting in an increase in exposure and/or vulnerability to climate change.

Proper integration of climate risks in decision-making processes will minimize the risk of over-, under-, and maladaptation. However, there is a close link with decision-making criteria (Figure 6.1): *What is the "right" level of adaptation? How climate resilient do we want our actions to be?* Willows and Connell (2003) suggest that decision makers can identify climate conditions that represent *benchmark levels of climate risk,* against which they can plan to manage. The benchmarks may be based on past experience of climate and weather events (floods, droughts, hurricanes, and so forth) or on expected climate futures. They *represent a defined threshold between tolerable and intolerable levels of risk,* and provide a basis for developing practical risk assessments (Willows and Connell, 2003). As information becomes available in the risk management process, benchmarks may be revisited. For example, it may turn out to be prohibitively expensive or unfeasible to stay within the original benchmark level of risk.

Timing and Uncertainty

The lifetime of a decision (for example, project, investment, strategy, or development plan) is an important consideration when determining whether climate adaptation is needed. Decisions on timing depend on the present value of the relative costs and benefits of undertaking adaptation at different points in time (Agrawala and Fankhauser, 2008). The discount factor (if greater than zero) and the prospect of cheaper and more efficient adaptation technologies and techniques in the future favor delayed action where possible. However, in a number of cases early action is justified and/or required. We discuss these next.

Long-lived Infrastructure

Many supply, transmission, and distribution investments are large and long lived. Early adaptation action for long-lived infrastructure investments will generally be less costly and more effective than retroactive maintenance and repairs or expensive retrofitting (ADB, 2005; Burton, 1996; IPCC 2007b; ECA 2009). Furthermore, substantial investments in energy infrastructure are ongoing or under way in most regions around the world and are expected to continue. The cumulative global capital required to meet projected energy demand up to 2030 is US$26 trillion in year-2008 U.S. dollars, or approximately 1.4 percent of GDP per year on average (IEA, 2009), and more than half of this is needed in developing countries.

When managing risk for long-lived energy investments it is important to consider the following questions:

- Is there sufficient knowledge to integrate climate risks in long-lived energy sector investments?
- Is additional time likely to:
  - Allow improved forecasting for key climate change variables?
  - Result in more refined modeling and methodologies?
  - Bring about an improved knowledge base for integration of adaptation measures in project and strategic decisions?
- Is it possible to postpone large/long-lived investment decisions?

Considerably more empirical literature is available on climate impacts on renewable energy (wind and hydropower) and thermal energy production,[3] but research is mostly silent on adaptation options and damages to buildings and electricity transmission and distribution networks, where decisions are typically climate influenced rather than climate based and planners may not be used to taking climate risks into account. There is also very little information on: damages from inundation and extreme weather events, the vulnerability of offshore energy exploitation and infrastructure, or indirect impacts on countries that rely on energy imports when supply channels are affected (for example, road and port damage or closure). Impacts in many developing regions of the world are understudied.[4]

Studies of the costs and benefits of energy adaptation are not available, although there are some estimates on damage costs in a recently published World Bank report on the Economics of Adaptation to Climate Change (EACC). The EACC estimates that total adaptation costs[5] for infrastructure for the period 2010–2050 are in the range of US$15–30 billion a year. For the higher estimate, total adaptation costs related to power generation (all sources) and electricity transmission and distribution are estimated at US$1.9 billion per year, ranging from US$0.1 billion in sub-Saharan Africa, the Middle East, and North Africa; US$0.2 billion in Latin America and the Caribbean; US$0.3 billion in South Asia; to US$0.6 in Europe and Central Asia and in East Asia and the Pacific (World Bank 2010b).

Systematic assessments—needed to enable strategic advice, establish guidelines and introduce regulatory adaptation measures—at national and regional levels are also scarce. There is limited capacity to model and project climate change and its impacts at local and regional scales.

It is clear that there is considerable scope to expand the knowledge base for long-lived energy sector investments. This could be facilitated by:

- developing guidance, information, and simple decision rules for climate risk integration for thermal power and transmission infrastructure (Willows and Connell, 2003);
- providing a framework for project-specific climate risk analysis of strategic and large projects;

- improving knowledge on gradual changes at regional and local scales as well as changes in the variability, frequency, and magnitude of extreme events;
- raising awareness of climate risks and adaptive responses; and
- ensuring access to relevant data and information.

Although the urgency of early integration of climate risks in energy supply and distribution decisions is clear, there is at least one important qualification. Delaying adaptation actions can be an appropriate risk management strategy, when additional time can reduce uncertainty (Willows and Connell, 2003).

Short-Term Adaptation Benefits and Actions That "Buy Time"

Measures that postpone energy sector investments often provide short-term adaptation benefits and can be characterized as no- or low-regret options (Burton, 1996) (Chapter 4, "Typology of Adaptation Responses"). The World Bank (2009c) finds, based on case studies, that between 40 percent and 68 percent of the loss expected to 2030 under severe climate change scenarios could be averted through adaptation measures whose economic benefits outweigh their costs. Examples of no-regret energy options in the African context include early warning systems, energy investment, diversification of energy generation, technology transfer, and energy efficiency (HELIO International, 2007).

Another example is demand-side management that can avoid or postpone investments in installed capacity and distribution network extensions (Bonneville and Rialhe, 2006). However, while many energy efficiency and broader demand-side management measures can be implemented at low or negative cost, providing win-win[6] investment opportunities, they face significant barriers to implementation (for example, behavior, policy, institutional). A study of power sector institutions in 24 countries in sub-Saharan Africa concluded that inefficiencies and below-cost prices for power generate substantial hidden costs amounting to an average of 1.8 percent of GDP in the region, and as high as 4 percent of GDP in some countries (Eberhard et al., 2008).

The ECA (2009) includes an interesting case study from Tanzania on the effects of future climate-related droughts on health and power risks. It constructs a cost curve for power measures illustrating that it is possible to close most of the expected climate-induced shortfall in power production by implementing energy efficiency measures at a negative cost for the country. It also finds that reducing spillage at hydro stations, thereby improving the load factor, could enable a significant increase in power supply for almost zero cost. The methodology employs a hands-on approach that generates relatively quick and rough estimates of the costs and benefits of various adaptation options using plausible climate and socioeconomic scenarios. It provides a basis for decision makers to identify, compare, and prioritize a range of cost-effective adaptation options that would be feasible within their given social, institutional, and economic context. It supports integration of energy-related climate risks in local, sectoral, and national agendas.

Strategic Adaptation Priorities

Strategic adaptation and policy decisions are made at the local, sector, and national levels. Appendix L illustrates government-led adaptation initiatives for energy systems and gives examples of regional and national energy adaptation assessments. Concerted efforts have mainly been undertaken in high-income countries, although the ESMAP pilot initiative will assist systematic and high-level energy system adaptation action in a number of other countries (Appendix L).

Policy-oriented and research literature agree that energy diversification is a strategic adaptation priority. Heavy reliance on hydropower—as exemplified by the Albania and East Africa cases (Appendix L)—creates significant vulnerability to climate change and is a feature that many low- and middle-income countries have in common. A study of Ho Chi Minh City in Vietnam (ADB, 2010) confirmed that a broader mix and balance in energy-generating options would support climate resilience, recognizing the value of diversity in promoting security and stability of supply.

Going forward, climate impacts will be felt most urgently at the local level, where many energy-related decisions are made. HELIO International (2007) recommends giving stronger attention to "bottom-up" approaches that focus on local resilience strategies and localized energy planning. The ECA (2009) also emphasizes the local level, recommending that effective climate risk assessment should be built on multiple local assessments rather than the extrapolation of a few local assessments to the national level.

Mainstreaming Climate Risk Management into Energy Planning

> *There is a tall wall between our scientists and our decision makers. Scientists do their research and lob their information over the wall, hoping that somebody on the other side will catch it in receptive hands and act on it. However, what is on the other side of the wall is a big pile of papers and information that the decision makers pay no attention to* (Jonathan Foley, 2010).

This section discusses options to fill knowledge, information, awareness and capacity gaps for climate risk management in the energy sector. It highlights the role of governments and institutions at the local, national and international levels.

Scientific Knowledge

Among the knowledge gaps, the lack of capacity to model and project climate impacts at local and regional scales (for gradual changes and changes in variability) is perhaps the most prominent. Government institutions and international research communities have the important task of filling this gap. Quoting Ram (2009), "*a major need in any area of technology deployment, including energy, is risk research prioritization to best fill gaps in the knowledge base or to understand more adequately the uncertainties that surround the risk problem at stake.*" According to Ram (2009), the following considerations should be taken into account when prioritizing risk research:

- How far can the risk be reduced through further research and in what timeframe?
- How deep are the uncertainties? Do they arise from data needs, a modeling problem, or do we basically not have a scientific understanding of the risk phenomena?
- How do the uncertainties interact with the profile of the risk—where will progress or reducing uncertainties most contribute to reducing overall risk?

To balance these aspects, the following principles may be considered:

- Knowledge needs of various decision makers and stakeholders.
- The cost-effectiveness and likelihood of risk reduction, given large uncertainties.
- Investments in decisions with short-term payoffs versus high-risk/high-gain longer-term research.

Box 6.3 identifies candidate areas for priority research, many of which require interdisciplinary efforts by scientists, energy experts, and economists.

Guidance for Decision Makers

Effort is needed to translate scientific data and knowledge into information relevant to decision making on adaptation. Further, the capacity of decision makers at various levels could be supported by providing:

1. Maps:
   - Hydro-meteorological mapping
   - Hazard maps for droughts and floods
   - Coastal maps with a 1-m altitude contour
   - Mapping of hydro plants that should expand their capacity due to projected improvements in river flow regimes
   - Siting maps for:
     - new hydropower plants that take projected mean changes and seasonal variability in river flows into account
     - wind power plants that take projected changes in wind speeds, floodplains, and area impacted by sea level rise into account
     - biomass power plants to prevent siting biomass power plants in floodplains and areas impacted by sea level rise
     - solar power, taking into account projected changes in cloud cover

Box 6.3. Candidate Areas for Priority Energy-Climate Research

- Research and assessment of extreme weather events, including strategies for reducing and recovering from impacts
- Research and assessment of the potential, cost, and limit of adaptation for supply and end-use infrastructure
- Improve information on the interactions between water demand and use where the quantity and timing of surface water discharge is affected by climate change
- Improve awareness of climate change and local climate variability for wind and solar power technologies
- Develop strategies to increase the resilience of coastal and offshore oil and gas production and distribution systems to extreme weather events
- Improve understanding of the benefits of regional capacity and distributed electricity generation for coping with climate impacts
- Research on end-use energy efficiency, particularly on technologies and practices that save cooling energy and reduce electrical peak load
- Research the implications of changing patterns of energy use for regional supply institutions
- Improve understanding of the effects of changing climate on renewable and fossil-fuel-based energy development, market penetration, and regional energy balances

Source: Wilbanks et al., 2008

- thermal power plants at sites with sufficient cooling water availability over the next 50 years (or the lifetime of the plant)
- mines that consider projected flooding and drought-prone areas

2. Guidelines and plans:
   - Guidelines on choosing locations for new power plants, taking into account climate change impacts
   - Guidelines for power plant robustness with regard to storms, floods, and heat waves
   - Guidelines for storm-proofing power plants and distribution and transmission infrastructure to make sure that the infrastructure withstands the highest wind speed that is likely to occur over the lifetime of the investment

Economic Assessment

Order-of-magnitude estimates of likely climate-related impacts on societies and economies are an effective way of catching the attention of central decision makers at international, national, and local levels. At present, energy-focused estimates of macro-economic impacts, the economic value of damages, and the benefits and costs of adaptation policies are limited. The World Bank study on the Economics of Adaptation to Climate Change (EACC) is the only example providing global and regional estimates of the cost of adapting power generation, transmission, and distribution infrastructure (World Bank, 2010b). At a country level, Eberhard et al. (2008) estimate the climate-related impacts of droughts on hydropower production and GDP for selected countries in sub-Saharan Africa, de Bruin et al. (2009) estimate the costs and benefits of energy adaptation options for the Netherlands, and the ECA (2009) includes a case study and cost curve for power sector adaptation in Tanzania. There is analysis of energy expenditure for cooling and heating resulting from climate change (see IPCC, 2007b, chapter 17.2 for an overview[7]), but this is mostly focused on North America and OECD countries.

Economic assessments need to be expanded at all levels, including detailed assessments of the costs and benefits of adaptation for site-specific investments and national/sector policies. The ECA (2009) approach could be applied for energy systems.

Integrated Development

An effective adaptive response requires that energy systems are considered in the context of development. HELIO International addresses energy resilience from the perspective of poverty and livelihood vulnerability, providing an example that is particularly relevant for low-income countries. Cross-sector links are also important when faced with competing uses of water, trans-boundary water resources, or tradeoffs between, for example, bio-energy production and food security (Chapter 4, “Integrated Planning”).

Further mitigation strategies to reduce GHGs also need to be resilient to the effects of climate change, presenting one area where further studies seem pertinent. There are overlaps between energy sector mitigation and adaptation policies and actions. Energy diversification, demand-side management, and energy efficiency, for example, support adaptation as well as mitigation. But there can be tradeoffs. Changing climate parameters may increase energy demand and consumption (for example, for cooling and heating), and mitigation policies that hinge on larger shares of renewable energy sources are very likely to affect risk management practices, to influence technology research and development, and to affect energy choices (Wilbanks et al., 2008). Moreover, if mitigation policies fail to integrate climate impacts on renewable energy sources, this could impose severe risks of maladaptation.

Notes

1. 3C refers to the Consortium's name, "Combat Climate Change," and not to a target maximum global temperature increase to avoid "dangerous anthropogenic interference with the climate system."
2. In the literature, the concepts of climate risk management and mainstreaming, climate proofing, and climate resilience are often used interchangeably, and the concepts are closely related (see, for example Olhoff and Schaer [2010] for a discussion). We focus on and consistently use the concepts of climate risk management and climate resilience. The climate risk management approach uses techniques that are particularly relevant for energy system adaptation issues.
3. Other energy sources include solar power, wave, tidal, and geothermal energy. However, there is very limited empirical research on climate implications for solar power and potential adaptive responses (Mideksa and Kallbekken, 2010). There is little relevant literature on wave, tidal, and geothermal energy sources. Peer-reviewed literature on bioenergy is scarce.
4. For example, though there is substantial research on climate impacts on wind power, geographical coverage is uneven (see, for example, Mideksa and Kallbekken, 2010). Studies focus on the North Sea (Sood and Durante, 2006); the Nordic region (Fenger, 2007); northern Europe (Pryor et al., 2005a, b, c; Pryor and Barthelmie, 2010); the UK (Cradden et al., 2006); Ireland (Lynch et al. 2006); the Eastern Mediterranean (Bloom, et al. 2008); and continental and northwest United States (Breslow and Sailor, 2002; Sailor et al., 2008). Apart from the U.S. studies, they indicate a small to moderate increase in wind power potential, with increased wind speed in the winter and decreased wind speed in the summer. There are few or no studies providing detailed analysis of changes in extreme winds on wind power potential (Mideksa and Kallbekken, 2010) that could have implications for turbine design optimization.
5. The adaptation cost is computed as the additional cost of constructing, operating, and maintaining baseline levels of infrastructure services under the new climate conditions projected by two global climate models, the National Centre for Atmospheric Research (NCAR) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) models, for the 2010–2050 period.
6. Actions that are justifiable even in the absence of climate change.
7. More recent additions to this literature include Mirasgedis et al. (2007) for Greece and Mansura et al. (2008).

CHAPTER 7

Near-term Actions to Support Adaptation

The energy supply chain is vulnerable to the consequences of global warming. It is affected by hydro-meteorological and climate factors that include temperatures, rainfall, cloudiness, radiation, wind speeds, storms, hail, lightning, river volumes, floods, droughts, ground conditions and discharge, ocean waves, and tides. Though potential climate impacts have been recognized strongly within the energy sector, focus has mainly as a source for greenhouse gas emissions rather than as a sector vulnerable to its impacts.

To date, decision makers have focused on maximizing energy supplies to satisfy industrial and societal demand for energy while managing the risks perceived to be of immediate concern. All available evidence suggests that managing the risks posed by current and future climate is not an optional add-on but a necessary management and planning concern that is likely to become increasingly important as the consequences of climate change materialize.

Adaptation *in toto* is an expansive area covering many sectors and socioeconomic structures. Adaptation has developed slowly under the United Nations Framework Convention on Climate Change (UNFCCC), although it has been given higher priority under the 2007 Bali Action Plan[1] (UNFCCC, 2008).

While adaptation to these impacts is likely to involve a drawn out process requiring major investments and strategic decisions, some actions to help mainstream climate considerations into energy sector planning and management are available in the short term.

- **Support awareness and knowledge exchange**: There is a need to disseminate and learn from the increasing data and knowledge of climate impacts on the energy sector, and their management. To be able to take informed actions, it will be important to: (a) support better awareness of these issues with public and private decision makers, and (b) support access to state of the art data on the consequences of climate destabilization.
- **Undertake climate impacts needs assessment**: Location specific adaptation requirements are dependent on an analysis of impacts. Climate impact analysis is the first step toward the development of adaptation strategies.

  Such an assessment should quantify the impacts, and hence risks, and data and information needs through the energy life cycle to guide adaptation practice in any country. It should incorporate and critique existing practices and potentially include an assessment of the associated costs of impacts, and of consequences if climate risk management is not applied.
- **Develop project screening tools**: Develop templates to screen individual energy projects for climate vulnerability and risks, either retrospectively or during

project planning and implementation. This should particularly target strategic and large-scale projects. Develop supporting guidance, information, and simple decision rules for climate risk integration into decision making (for example how to choose locations for new power plants, taking into account climate change impacts, or power plant robustness to extreme events). Simulation modeling could support the development of pertinent "what-if" scenarios.

- **Develop adaptation standards for the energy sector**: Such standards should cover engineering matters and information requirements. Though the development of standards is beyond the remit of the UNFCCC, it could be handled through the energy sector itself, through international organizations such as the UN, International Energy Agency (IEA), International Renewable Energy Association (IRENA), and universities or research institutions. The International Civil Aviation Authority could provide a model framework for an organization tasked with developing adaptation standards relevant to the energy sector (Appendix I). Agreement on, and enactment of, standards would require coordination with other pertinent organizations.

  Some examples include: standards for robust coastal infrastructure that take into account the anticipated strength of extreme weather events; revised zoning standards to minimize climate risks for future assets; and construction standards in traditional permafrost areas to accommodate changes in soil structural characteristics.
- **Revisit planning timeframes and the use of historic data for future investments:** Traditional planning approaches that use historic data may need to be revisited an adjusted to reflect anticipated climate trends. There is a need to review and implement changes in the use of historic data as a basis for future energy investments (for example, introduce weighting that reflects recent climate trends and adjust the shelf-life of investments where energy resource endowments are affected by climate change).
- **Address potential climate impacts when retrofitting existing infrastructure:** Planned retrofits of existing assets need to address climate impacts. Already available methodologies, such as energy or environmental audits, can help identify any needed changes in operational and maintenance protocols, structural changes and/ or the relocation of existing plants.
- **Implement specific adaptation measures:** Adaptation measures can include a range of off-the-shelf (for example, the use of reverse osmosis units to address seawater intrusion in cooling water) and innovative solutions. In the latter case, this requires investment in pilot or demonstration projects to illustrate the costs and benefits of alternative adaptation strategies; and subsequent support to integrate results into large scale operations. There is also a need to expand the knowledge base through actions that:
  - Explore the interaction between water demand and use, and cross-sector and regional energy and water balances.
  - Better understand the impacts of climate change on renewable resource potential (for example, wind, solar, biomass).
  - Explore synergies and tradeoffs between climate mitigation and adaptation strategies for the energy sector.

- Identify options (technological and behavioral) to save cooling energy and reduce electrical peak load demand.

- **Identify policy instruments** needed to support climate impact management—for example, policy instruments that support internalization of adaptation issues in energy operations; or, incentives to adjust planning and operational process to reflect longer timeframes.
- **Support capacity building:** Increase the capacity of key stakeholders, including energy sector policy makers, regulators, and operators, for climate risk management; in particular "bring policy makers up to speed".

Climate Information Networks

Investments in observations and in weather and climate services may be required to support decision making. Information gaps could be filled in collaboration with existing international organizations and programs, such as the WMO, the Global Climate Observing System (that provides support for climate assessments and projections in all parts of the world),[2] and the Global Framework for Climate Services[3] (Appendix M).

However, national hydro-meteorological service centers may not have the resources to fulfill all energy sector observational requirements; many countries with declining networks place priority on meeting minimum WMO standards. Though some meteorological prediction centers are establishing "seamless"[4] prediction approaches through the use of a consistent set of models across time scales, the more important issue in the energy sector is a "seamless" approach to decision making and risk management across time scales. Limited consideration has been given to the concept of seamless decision making to date, but an example from the energy sector is found in planning and managing a hydroelectric scheme using water predictions across all time scales.[5]

Although basic hydro-meteorological/climate observation networks are expensive to develop and maintain, they can provide essential inputs into planning for climate change. Options to improve the quality and flow of such information to the energy sector are provided next.

- **Observation Networks.** In developing countries a key priority is to return deteriorating observation networks to minimum WMO standards. This will provide broader weather and climate benefits (including in calibrating satellite measurements) for the energy sector rather than immediate gains given the location-specific information needs for infrastructure-based decisions.

  However, energy information could be improved if basic weather and climate networks are provided with platforms (ideally automated) or supported with ongoing maintenance in areas with immediate benefit to the energy sector. Priority could be given to creating subsidiary hydro-meteorological networks (again ideally automated, perhaps including upper-air and offshore measurements) that would benefit current and planned energy sector activities.

  Assistance might also be provided to improve communications and capacity not only for a country to collect its own data but also to provide data to the international community and to receive and process data, including those from re-analyses and satellites.
- **Support Data Rescue and Archiving.** There are various programs supporting data rescue, including one in WMO,[6] but the need is extensive. Paper records

need to be digitized, and documented climate information needs to be recovered, such as from missionaries' diaries. Support is needed to build secure digitized data archives, ideally to a common standard, and to ensure archives are accessible and protected from possible destruction. If appropriate, extended climate series might be created using proxy data.

- **Upgrade Resources for Weather and Seasonal Forecasts and Outlooks.** In many countries resources for the delivery of forecasts, and the development and use of forecast models for the energy sector, could be upgraded substantially. Support needs include:
  - Facilities for receipt and processing of forecast information.
  - Capacity building for forecasters to interpret and verify advanced forecasts, including from ensembles.
- **Build Capacity to Prepare Projections of Climate and Associated Impacts.** Access to IPCC projections is straightforward, but developing countries require substantial capacity building support to process, interpret, and produce national-level impact projections. The UNFCCC promotes adaptation through National Adaptation Programmes of Action (NAPAs)[7] and the Nairobi Work Programme (UNFCCCNWP).[8] But only 44 countries have submitted NAPAs, most of which do not cover adaptation in the energy sector, and the benefit realized by most countries from the UNFCCCNWP has been fairly limited to date. The UNFCCCNWP nevertheless provides a framework for capacity building. It includes national downscaling using RCM. RCMs can be an invaluable tool provided recognition is made of the inherent uncertainties (see Chapter 5, "Access to Predictions").
- **Support Cross-Sector Dialogue.** Facilitate engagement between weather and climate information providers and energy users (possibly at a regional level), with the aim of providing early warning and advisory climate services.

Notes

1. The Bali Action Plan was adopted at the 13th conference of the parties to the UNFCCC (UNFCCC, 2008). It committed to launch a comprehensive process to enable the full, effective, and sustained implementation of the Convention through long-term cooperative action, now, and up to and beyond 2012. This included: a shared vision for long-term cooperative action, including a long-term global goal for emission reductions, to achieve the ultimate objective of the Convention; enhanced national/international action on mitigation of climate change; enhanced action on adaptation; enhanced action on technology development and transfer to support action on mitigation and adaptation; and enhanced action on the provision of financial resources and investment to support action on mitigation and adaptation and technology cooperation.
2. http://www.wmo.ch/pages/prog/gcos/.
3. http://www.wmo.ch/hlt-gfcs/documents/WCC3GFCSbrief_note_en.pdf.
4. Satisfying requirements to receive consistent information, both historical and predictive, for many different time scales.
5. A case in point is provided by the devastating Mozambique floods of 2000, caused in part by insufficient planning to handle the water volumes involved but exacerbated by dam water and generation management plans that forced operators to leave water release until far too late for downstream populations.
6. http://www.wmo.ch/pages/prog/wcp/wcdmp/dare/index_en.html.
7. National Adaptation Programmes of Action - http://unfccc.int/cooperation_support/least_developed_countries_portal/items/4751.php.
8. http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php.

Glossary

This report draws on the definitions and terminology used by the IPCC's Fourth Assessment Report. To support the reader, selected definitions are reproduced here based on the glossaries published in the contributions of Working Groups of I, II, and III to the IPCC AR4 (IPCC, 2007a, 2007b, 2007c, 2007d).

Adaptation Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected *climate change* effects. Various types of adaptation exist, for example, *anticipatory* and *reactive*, *private* and *public*, and *autonomous* and *planned*. Examples are raising river or coastal dikes, the substitution of more temperature-shock-resistant plants for sensitive ones, and so forth

Adaptive capacity The whole of capabilities, resources, and institutions of a country or region to implement effective adaptation measures.

Climate In a narrow sense, usually defined as the average weather, or, more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*. In various parts of this report different averaging periods, such as a period of 20 years, are also used.

Climate change Refers to a change in the state of the *climate* that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or *external forcings*, or to persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use*. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also *Climate variability*.

Climate model A numerical representation of the *climate system* based on the physical, chemical, and biological properties of its components, their interactions and *feedback* processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity—that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parameterizations are involved. Coupled *atmosphere–ocean general circulation models (AOGCMs)* provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution toward more complex models with interactive chemistry and biology (see IPCC 2007a, Chapter 8). Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal, and inter-annual climate predictions.

Climate prediction A climate prediction or *climate forecast* is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, for example, at seasonal, inter-annual, or long-term time scales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. See also *Climate projection, climate scenario*.

Climate projection A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from *climate predictions* in order to emphasize that climate projections depend upon the mission/concentration/radiative forcing scenario used, which is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Climate scenario A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information, such as data about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Climate sensitivity In IPCC reports, *equilibrium climate sensitivity* refers to the equilibrium change in the annual mean *global surface temperature* following a doubling of the atmospheric *equivalent carbon dioxide concentration*. Due to computational constraints, the equilibrium climate sensitivity in a climate model is usually estimated by running an atmospheric general circulation model coupled to a mixed-layer ocean model, because equilibrium climate sensitivity is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The *transient climate response* is the change in the *global surface temperature*, averaged over a 20-year period, centered at the time of atmospheric carbon dioxide doubling, that is, at year 70 in a 1%/yr compound carbon dioxide increase experiment with a global coupled climate model. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing.

Climate variability Refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, and so forth) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also *Climate change*.

El Niño-Southern Oscillation (ENSO) The term *El Niño* was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the *Southern Oscillation*. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is collectively known as *El Niño-Southern Oscillation*, or *ENSO*. It is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called *La Niña*.

Extreme weather event An event that is rare at a particular place and time of year. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function. By definition, the characteristics of what is called *extreme weather* may vary from place to place in an absolute sense. Single extreme events cannot be simply and directly attributed to anthropogenic climate change, as there is always a finite chance the event in question might have occurred naturally. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an *extreme climate event*, especially if it yields an average or total that is itself extreme (for example, drought or heavy rainfall over a season).

Hydrological cycle The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapor, condensates to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and, ultimately, flows out into the oceans, from which it will eventually evaporate again (AMS, 2000). The various systems involved in the hydrological cycle are usually referred to as *hydrological systems*.

Impact assessment (climate change) The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of climate change on natural and human systems.

Impacts (climate change) The effects of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts:

- *Potential impacts*: all impacts that may occur given a projected change in climate, without considering adaptation.
- *Residual impacts*: the impacts of climate change that would occur after adaptation.

Patterns of climate variability Natural variability of the climate system, in particular on seasonal and longer time scales, that predominantly occurs with preferred spatial patterns and time scales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called *regimes*, *modes*, or *teleconnections*. Examples are the North Atlantic Oscillation (NAO), the Pacific-North American (PNA) pattern , the El Niño-Southern Oscillation (ENSO), the Northern Annular Mode (NAM; previously called Arctic Oscillation, AO), and the Southern Annular Mode (SAM; previously called the Antarctic Oscillation, AAO). Many of the prominent modes of climate variability are discussed in Chapter 3.6 of the Working Group I Report.

Resilience The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.

Runoff That part of precipitation that does not evaporate and is not transpired, but flows over the ground surface and returns to bodies of water. See *Hydrological cycle.*

Sensitivity The degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be *direct* (for example, a change in crop yield in response to a change in the mean, range, or variability of temperature) or *indirect* (for example, damages caused by an increase in the frequency of coastal flooding due to sea level rise). This concept of sensitivity is not to be confused with *climate sensitivity*, which is defined separately above.

Storm surge The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.

Storm tracks Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the *regions* where the main tracks of extratropical disturbances occur as sequences of low-pressure (cyclonic) and high-pressure (anticyclonic) systems.

Uncertainty An expression of the degree to which a value (for example, the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts.

Vulnerability The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Water stress A country is water stressed if the available freshwater supply relative to water withdrawals acts as an important constraint on development. In global-scale assessments, basins with water stress are often defined as having per capita water availability below 1,000 m3/yr (based on long-term average runoff). Withdrawals exceeding 20 percent of renewable water supply have also been used as an indicator of water stress. A crop is water stressed if soil available water, and thus actual evapotranspiration, is less than potential evapotranspiration demands.

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Appendixes

Appendix A. IPCC Emissions Scenarios and Confidence Levels

IPCC Emissions Scenarios

In 1992, for the first time, the IPCC released emission scenarios for use in driving global circulation models to develop climate change scenarios.

In 1996, the IPCC decided to develop a new set of emissions scenarios (SRES), which provided input to the IPCC's Third Assessment Report (TAR) in 2001. The SRES scenarios were also used for the AR4 in 2007. Since then, the SRES scenarios have been subject to discussion because emissions growth since 2000 may have made these scenarios obsolete. It is clear that the IPCC's Fifth Assessment Report will develop a new set of emissions scenarios.

The SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. None of the scenarios includes any future policies that *explicitly* address climate change, although all scenarios necessarily encompass various policies of other types and for other sectors. The set of SRES emissions scenarios is based on an extensive literature assessment, six alternative modeling approaches, and an "open process" that solicited wide participation and feedback from many scientific groups and individuals. The SRES scenarios include a range of emissions of all relevant greenhouse gases (GHGs) and sulfur and their underlying driving forces.

As an underlying feature of all emissions scenarios, the IPCC developed four different narrative storylines to describe the relationships between emission-driving forces and their evolution over time (Figure A1). Each storyline represents different demographic, social, economic, technological, and environmental developments. Each emissions scenario represents a specific quantitative interpretation of one of the four storylines. All of the scenarios based on the same storyline constitute a scenario "family."[1]

- **A1 storyline** and scenario family describes a future world of rapid economic growth, global population peaks by mid-21st century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes of the A1 storyline are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: *fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).*
- **A2 storyline** and scenario family describes a rather heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Global population increases continuously. For the most part, economic development is regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines.

Figure A1. Schematic Illustration of SRES Scenarios

Source: IPCC, 2000, modified.

- **B1 storyline** and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- **B2 storyline** and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with global population continuously increasing at a rate lower than that of A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. Though the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The overview in Table A1 summarizes the likely temperature changes under each of the scenarios described. It shows that B2 would lead to a temperature change of approximately 2.4°C toward the end of the century, under A1B the temperature change is estimated to be 2.8°C, while A2 is more extreme with a 3.4°C projected change.

It is important to note that the projected surface temperature changes toward the end of the 21st century exhibit a broad range of likely estimates, as shown by the bars next to the right panel of Figure A2.

Table A1. Projected Global Average Surface Warming and Sea Level Rise at the End of the 21st Century According to Different SRES Scenarios

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:

a) Temperatures are assessed best estimates and *likely* uncertainty ranges from a hierarchy of models of varying complexity as well as observational constraints.

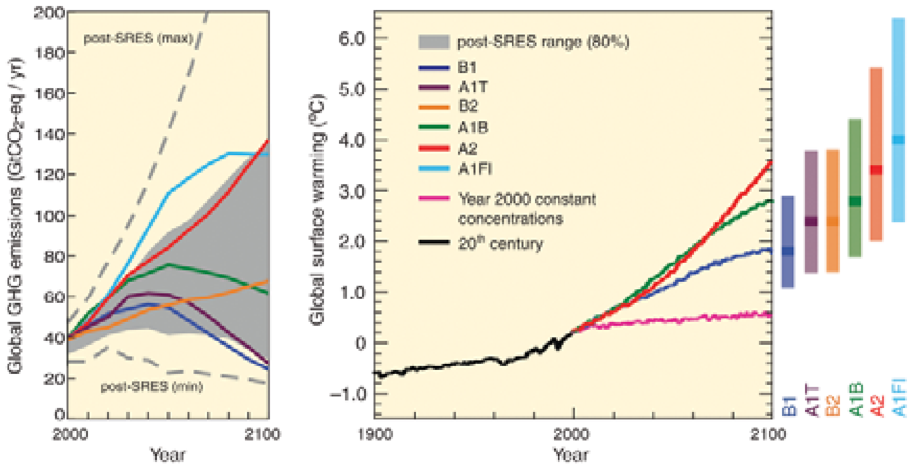
b) Year 2000 constant composition is derived from Atmosphere-Ocean General Circulation Models (AOGCMs) only.

c) All scenarios above are six SRES marker scenarios. Approximate CO_2-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the Working Group I TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550ppm, respectively.

d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5°C.

Source: IPCC, 2007d.

Figure A2. Scenarios for GHG Emissions from 2000 to 2100 (In the Absence of Additional Climate Policies) and Projections of Surface Temperatures



Source: IPCC, 2007d.

Note: **Left Panel:** Global GHG emissions (in $GtCO_2$-eq) in the absence of climate policies: six illustrative SRES marker scenarios (colored lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (gray-shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO_2, CH_4, N_2O, and F gases.

Right Panel: Solid lines are multi-model global averages of surface warming for scenarios A2, A1B, and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The pink line is not a scenario, but is for AOGCM simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090–2099. All temperatures are relative to the 1980–1999 period.

IPCC Statements of Confidence

Quoting the IPCC AR4 Guidance Note on Uncertainty (IPCC, 2005):

> ***Likelihood**, as defined* [below], *refers to a probabilistic assessment of some well defined outcome having occurred or occurring in the future.*
>
> *The categories defined in this table should be considered as having 'fuzzy' boundaries. The central range of this scale should not be used to express a lack of knowledge… There is evidence that readers may adjust their interpretation of this likelihood language according to the magnitude of perceived potential consequences.*

Terminology	Likelihood of outcome
Virtually certain	>99% probability of occurrence
Very likely	>90% probability
Likely	>66% probability
About as likely as not	33 to 66% probability
Unlikely	<33% probability
Very unlikely	< 10% probability
Exceptionally unlikely	< 1% probability

Source: IPCC 2005.

A ***level of confidence*** was defined as well, and the terminology is reproduced below and can be used to characterize uncertainty that is based on expert judgment as to the correctness of a model, an analysis, or a statement. The last two terms in this scale are reserved for areas of major concern that need to be considered from a risk or opportunity perspective, and the reason for their use should be carefully explained.

Terminology	Degree of confidence in being correct
Very High confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Source: IPCC 2005.

Notes

1. For each storyline, several different scenarios were developed using different modeling approaches to examine the range of outcomes arising from a range of models that use similar assumptions about driving forces.

Appendix B. Re-analyses and General Circulation Models

Limitations of Re-analyses Products

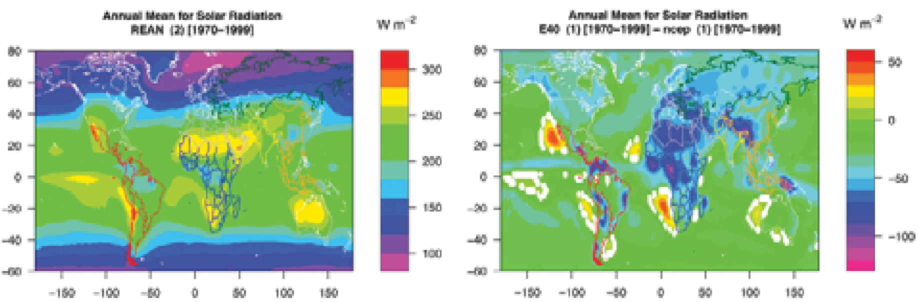
It is important to realize that despite being very widely used (in excess of 7,000 citations between the two considered here), re-analyses have limitations. Such limitations are detectable by looking at the differences between variables in two re-analyses. Some of these differences can be substantial. In the case of annual global solar radiation, for instance, these are as large as 100 W m^{-2} over areas such as Central Africa (Figure B1, right), therefore almost as big as the signal itself (Figure B1, left).

The situation is further complicated by the fact that while photovoltaic panels (PV) respond to global radiation, CSP devices require mainly the direct beam component of the global radiation. The assessment of the global radiation components is a current research topic and products available are at a preliminary stage.

It is clear therefore that the planning of solar power plants would carry a high level of estimated output uncertainty in such circumstances. In principle it would clearly be preferable to use direct measurements for this purpose, but in developing countries these may not be available and re-analyses (or other model simulation) thus become the only or principal tool available for assessing solar power output. Indeed, it is likely that the paucity of observations, which represents a strong constraint to the output of the re-analyses, is responsible for the marked discrepancy in the re-analyses in such poorly observed regions.

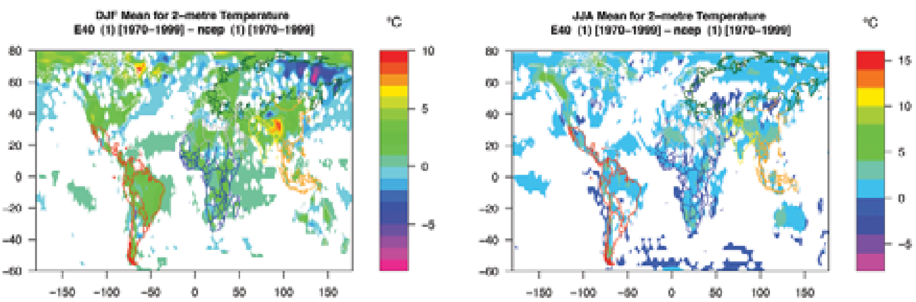
Similarly to solar radiation, the average 2-meter temperatures for DJF and, to a lesser extent, JJA are also affected by sizeable differences between the two re-analyses (Figure B2). Note that again the larger differences are present over the World Bank regions; a sign that even for this comparatively well-observed variable, re-analyses can diverge over less-well-observed, and possibly poorer, regions.

Figure B1. Global Solar Radiation (Left) Average of the Two ERA-40 and NCEP/NCAR Re-analyses and (Right) Their Difference



Source: Generated by authors.
Note: Large differences are present over most of Africa, South America, and Asia.

Figure B2. Difference in Mean Two-Meter Temperature between the ERA-40 and NCEP/NCAR Re-analyses for DJF (Left) and JJA (Right)



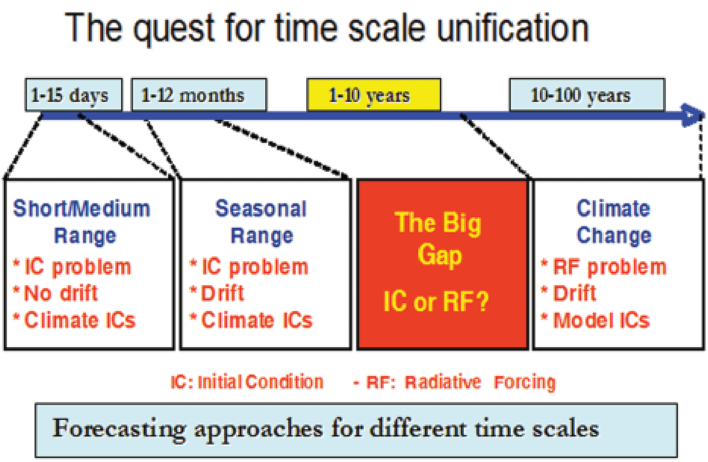
Source: Generated by authors.
Note: Large differences are present particularly in DJF over Siberia and North of India.

Predicting Weather, Simulating Climate: The Role of General Circulation Models

The most complete way to simulate weather and climate processes, be it for numerical weather predictions, seasonal climate forecasts, climate change scenarios, or re-analyses, is by means of (coupled) GCMs. In such models the Earth system is subdivided into cells of sizes varying according to the purpose of the model, namely from 10 km to 100 km numerical weather predictions for climate change scenarios. Dynamic and thermodynamic physical relationships are solved numerically, often on large supercomputers, for each cell as well as for the interactions amongst cells. GCMs calculate atmospheric, land, and oceanic parameters, such as temperatures and winds, and their changes in time, at the surface and at various levels in the atmosphere, over the land and in the oceans.

Different components or attributes of the Earth system affect in specific ways physical processes relevant to weather and climate. By isolating certain aspects of the Earth system, predictions of weather and climate at different lead times become a more tractable problem. Generally speaking, physical processes can be divided into fast ones (for example, atmospheric convection) and slow ones (for example, circulation of the deep ocean), with an essentially continuous spectrum of processes in between. Given the presence of this wide spectrum, choices about which process is more relevant for a particular purpose have to be made. Thus, for instance, it would be of little use to run a complex sea ice component to produce forecasts for tomorrow's weather, as the sea ice response is much longer than a day. Likewise, for a climate forecast several years hence, the precise details of today's weather are less relevant than for forecasts for the next few days/weeks. Viewed in a different way, one can distinguish between short to inter-annual range predictions for which initial conditions are essential (with diminishing importance with increasing lead time) and decadal projections for which boundary conditions (or radiative forcing effects) are dominant. The following diagram (Figure B3) highlights the transitional time scale (that is, between 1 to 10 years). Indeed, this is a time range over which the relative importance of initial conditions versus radiative forcing shifts from one to the other (Collins and Allen 2002; Troccoli and Palmer, 2007).

Figure B3. A Schematic Representation of the Current Weather/Climate Forecasting Systems



Source: Troccoli, 2009.
Note: The figure emphasizes the relative importance of initial conditions and boundary conditions at the different lead times. As highlighted, the decadal lead time (from 1 year to, say, 10 years) represents a transitional time scale for which initial conditions may still be important but they compete with the radiative forcings effects. Also, model errors (drift) start to become apparent already in the seasonal time scale range but there are techniques to account for these.

So, although in principle a single system for all lead times would be desirable (and this is what some prediction centers are attempting to achieve), in practice predictions are made with built-for-purpose model configurations. However, as computers have become more powerful, enabling calculations to be run more quickly, so increasing detail has been included and cross-fertilization has been used often to improve models for these different applications.

In order to start a forecast (from, say, a few hours ahead to about one year) run with any model, it needs to be given an initial condition (a.k.a., "analysis"), that is, fields that describe the current state of the relevant components of the Earth system. Creating an analysis is a complex and costly task on its own, involving collecting data from around the world (in limited time for weather forecasting) and processing those data into the analysis through several stages, one of which is called "assimilation." Once the analysis is available the model can be run from it to produce a forecast. Through improvement in assimilation techniques and archiving of "late" data, historical re-analyses are produced nowadays that can provide the most consistent and detailed pictures of past global climate available for recent decades, information of great value to the energy sector.

Despite remarkable advances in models and computers, the models are not, nor ever will be, perfect. Equally, analyses inevitably contain errors, however carefully prepared. Both types of errors feed into the predictions, producing unavoidable inaccuracies; inaccuracies that cannot be measured from a single forecast run. The current typical approaches to alleviate these problems are: (i) to use an "ensemble" (that is, several predictions each slightly different from all others), or (ii) to combine several models using the so-called multi-model.

None of the (perhaps) 50 ensemble members/multi-model realizations will contain the "right" answer, and the only correct approach is to treat the ensemble as providing a probability distribution of forecasts. Taking an average across all ensemble members produces the optimal deterministic forecast, but use of this is never advisable without the additional information on the uncertainties revealed in the full ensemble.

IPCC/CMIP3 Models Used in This Report

The results from the following 15 models have been interpolated into a common grid (2.5 x 2.5 deg^2) and the results shown in this report are based mainly on an average of (up to) 15 models. Only differences between the future climate in the 30-year period 2050–2079 and a past period, 1970–1999, of similar length are shown. The 2050–2079 period has been chosen rather than an earlier one mainly because of data availability.

Even if in principle an earlier period would have been more appropriate for energy infrastructure whose lifetime is around 30 years, choosing a later period has its advantages too: differences amongst scenarios become more evident with longer lead times, and therefore "hotspots" can more easily be identified, in the assumption that trends are approximately linear (which may not be the case for variables such as clouds, radiation, wind). It should be noted that the accuracy of climate models is such that they should only be used for comparative studies (for example, differences among periods), and not for absolute assessment (not even for past periods).

1. BCM2 from the Bjerknes Centre for Climate Research, Norway, http://www.bjerknes.uib.no/default.asp?lang=2
2. CGCM3.1 from the Canadian Center for Climate Modelling and Analysis, http://www.cccma.bc.ec.gc.ca/eng_index.shtml
3. CM3 from the French Centre National de Recherches Météorologique, http://www.cnrm.meteo.fr/gmme/
4. Climate Model Mark 3.0 from the Australian Commonwealth Scientific and Industrial Research Organisation, http://www.csiro.au/science/EMM.html
5. CM2.1 from the US Geophysical Fluids Dynamical Laboratory, http://www.gfdl.noaa.gov/research/climate/
6. Version ER of the climate model of the NOAA Goddard Institute for Space Studies, http://www.giss.nasa.gov/research/modeling/gcms.html
7. CM3.0 of the Russian Institute for Numerical Mathematics, http://www.inm.ras.ru/inm_en_ver/index.htm
8. CM4 of the Institut Pierre Simon Laplace, http://www.ipsl.jussieu.fr/
9. MIROC3.2(MEDRES) of the Centre for Climate System Research of the University of Tokyo and the Frontier Research Centre for Global Change, http://www.ccsr.u-tokyo.ac.jp/ehtml/etest.shtml and http://www.jamstec.go.jp/frcgc/eng/
10. ECHAM5 from the German Max Planck Institute for Meteorology, http://www.mpimet.mpg.de/en/home.html
11. GCCM2.3.2a from the Japanese Meteorological Research Institute, http://www.mri-jma.go.jp/Dep/cl/cl.html
12. ECHO-G from the German Meteorological Institute of the Rheinische Friedrich-Wilhelms Universität Bonn, the Meteorological Institute of the Korean Meteorological Administration, and the Model and Data Group, Germany/Korea,

http://www.meteo.uni-bonn.de/index.en.html and http://www.metri.re.kr/metri_home/english/Introduction/uAboutE.jsp and http://www.mad.zmaw.de/
13. CCSM3 from the US National Center for Atmospheric Research, http://www.ccsm.ucar.edu/
14. HadCM3 from the UK Met Office, http://www.metoffice.gov.uk/research/hadleycentre/index.html
15. HadGEM from the UK Met Office, http://www.metoffice.gov.uk/publications/HCTN/HCTN_54.pdf

Sources of Uncertainty in IPCC/CMIP3 Model Results

In interpreting the results of this assessment it is important to be aware of the limitations of the climate change projections. Despite climate models being the most complete approach available for making projections, models are particularly challenged when used to provide detailed regional and national projections. Continual improvements are, however, made to these models, and the next set of data to be released in about a couple of years promises to considerably improve the current CMIP3 simulations, at least in terms of increased resolution. Other factors, including the future concentrations of atmospheric greenhouse gases, provide further uncertainties in the projections.

Modeling of the Earth System—The complexity of the Earth system is such that uncertainty in climate change projections is unavoidable. Partly because of limited computational resources and partly because of our limited knowledge about the interaction among all of the components of the Earth system (for example, sea ice interaction with atmosphere and ocean), many approximations and short- cuts need to be made to run climate change runs over long periods (100 years or more). One of the consequences is that regional details especially are not as accurate as global features, and therefore it is important not too over-interpret small-scale signals. However, interpretation is also dependent on the variable considered: precipitation, for instance, is a more variable field than temperature, and therefore statistics of the former are generally less significant (that is, smaller signal-to-noise ratio) than the latter.

Greenhouse Gas (GHG) Emissions and Concentrations—Changes in climate are dependent on future GHG concentrations. These are unknown, and will depend on human actions; the Kyoto Protocol and progress with UNFCCC and Conference of the Parties (COP) Intergovernmental Meetings will play a major role in determining levels of future anthropogenic emissions through international agreements. As precise future emissions and consequent atmospheric gas concentrations are unknowable, the IPCC uses a series of emissions scenarios in an attempt to bracket the likely range of reasonable possibilities, from noncurbing of the use of fossil fuels through to progressive conversion to energy generation from noncarbon sources. Future climate projections from all models are critically dependent upon the emissions scenario in use, although as a rule of thumb all indicate larger changes in global and regional temperatures given higher emissions; similarly, there is a tendency for projected total global rainfall to increase under higher emissions, but, as mentioned, projected regional rainfall changes are more complex and cannot be so easily summarized.

Two emissions scenarios have been used here and have been selected to bracket the range used by the IPCC. These are "typical" scenarios that provide a reasonable overview of all possibilities. To give an idea of the impact of these scenarios when combined with model uncertainties, the end-of-the-21st-century *globally averaged* temperature ranges in the projections by about 5°C. The two scenarios are named:

a) SRESA2: a high future emissions scenario that results in a *best estimate* global temperature change of ~3.4°C by 2100 (recent measurements suggest that actual emissions to date have *exceeded* those assumed in this worst-case scenario).
b) SRESB1: a relatively low future emissions scenario, ~1.8°C by 2100.

These are referred to sometimes as A2 and B1, respectively. Although runs for both scenarios are presented, the A2 results, which depict the greatest simulated changes, are the ones most closely fitting scenario reality since these models were run.

Available Statistics/Variables

Only a very small selection of available statistics/variables combinations has been presented in the modeling for this report. Table B1 indicates what additional results may be available.

Table B1. Possible Additional Modeling Options

Type	List
Model	ERA40, NCEP/NCAR, 15 CMIP3 models (see list above)
Variable	2-meter temperature, 10-m wind (and its components), 850-hPa wind (and its components), pressure, solar radiation, precipitation
Period	1971−2000 & 2050−2079 (results from other periods could easily be generated)
Statistics	Mean, standard deviation, 10th and 90th percentiles, linear regression (results for other statistics could be generated with minimal additional effort), changes in drought/flood statistics
Scenario	20th century, A2, B1 (results from other scenarios could easily be generated)
Season	Annual, DJF, MMA, JJA, SON
Time frequency	Yearly, monthly, daily (latter when available)

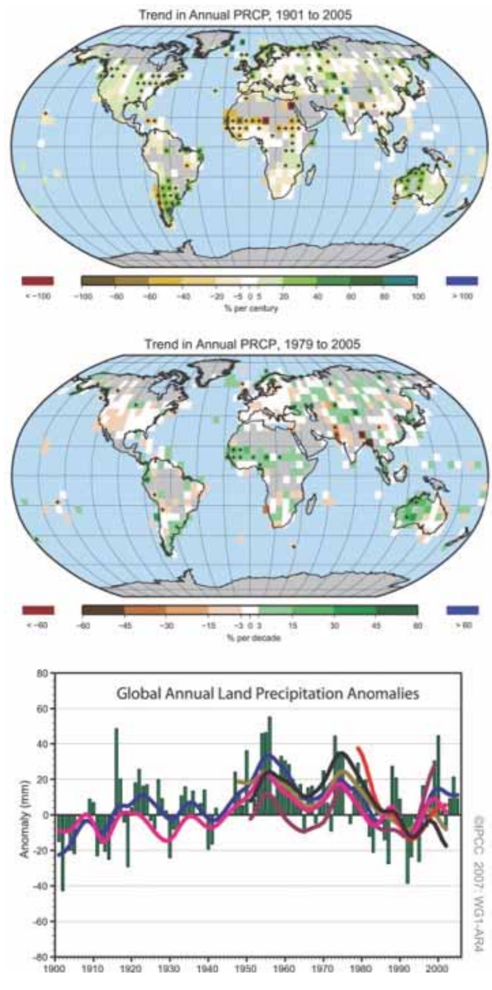
Source: Generated by authors.

Appendix C. Observed Trends in Precipitation and Sea Level Change

Observed Long-Term Trends in Precipitation

Long-term trends in precipitation amounts from 1900 to 2005 have been observed in some large regions (Figure C1); the observational records are mostly accessible in the extra-tropics. Significantly increased precipitation has been observed in the eastern parts of North and South America, northern Europe, and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa, parts of northern

Figure C1. Distribution of Linear Trends of Annual Land Precipitation Amounts over the Period 1901 to 2005 and 1979 to 2005



Source: IPCC, 2007a.
Note: The top picture shows the period 1901–2005 (% per century) and the middle picture the period 1979–2005 (% per decade). Time series of annual global land precipitation anomalies with respect to the 1961 to 1990 base period for 1900 to 2005. Areas in gray have insufficient data to produce reliable trends.

South America, the Caribbean, and parts of southern Asia. Precipitation is highly variable spatially and temporally, and robust long-term trends have not been established for other large regions. However, formal detection and attribution studies have now revealed that only the broad continental-scale patterns of observed change are consistent with the observed warming and can be attributed to anthropogenic effects (Zhang et al., 2007).

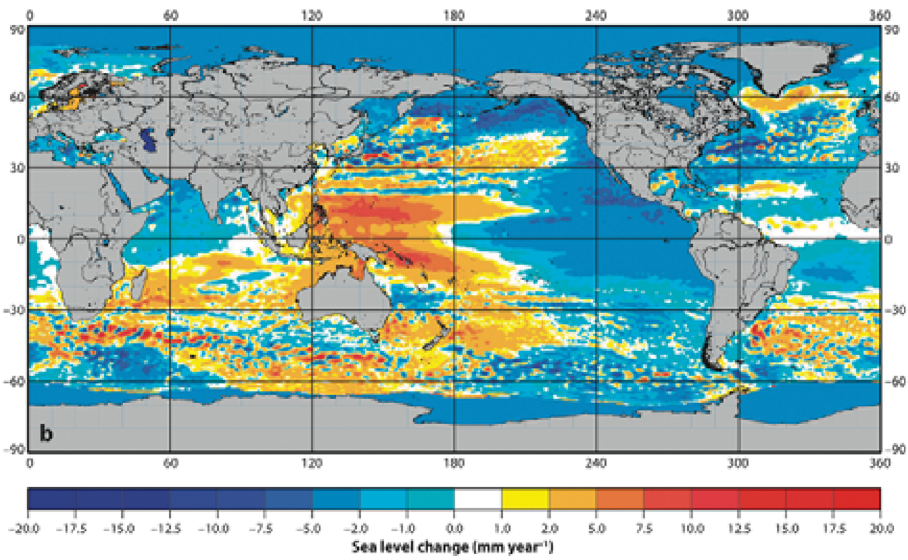
Substantial increases in heavy precipitation events have also been observed. It is likely that there have been increases in the number of heavy precipitation events in many land regions since about 1950, even in those regions where there has been a reduction in total precipitation amount. Increases have also been reported for rarer precipitation events (1 in 50-year return period), but only a few regions have sufficient data to assess such trends reliably.

Observed Sea Level Change

Sea level is a sensitive variable for climate, as it responds to changes in several components of the Earth system. For instance, as oceans warm up, sea level rises by thermal expansion; as glaciers or ice sheets melt due to increasing air temperature, sea level rises because of freshwater mass input to the oceans; modifications in the hydrological cycle lead to variations in river runoff, and ultimately to sea level change.

The causes of present-day sea level rise are attributable mostly to ocean thermal expansion in response to ocean warming (ca 30 percent) and to mass loss in mountain glaciers and ice sheets (ca 55 percent). Satellite altimetry has revealed considerable regional variability in the rates of sea level change with some regions, such as the western Pacific, and off southeast Africa, with sea level rise rates up to three times faster than the global mean (Figure C2). Such a nonuniform sea level trend is caused principally by differential ocean thermal expansion.

Figure C2. Spatial Trend Patterns of Observed Sea Level between January 1993 and December 2008 but With a Uniform Trend of 3.4 mm year^{-1} Removed



Source: Cazenave and Llovel, 2010.

Sea level rise is a difficult climate parameter to determine using climate models because it involves interactions between all components of the climate system (oceans, ice sheets and glaciers, atmosphere, land water reservoirs) on a wide range of spatial and temporal scales. Even the solid Earth through its elastic response to changing crust and mantle parameters, as well as water mass redistribution, affects sea level. Systematic monitoring of oceans, cryosphere, and land waters from in situ and space-observation systems are thus crucial to validate climate models, and hence improve future sea level projections (Cazenave and Llovel, 2010).

Appendix D. Projected Temperature and Precipitation Changes in Different Regions

For the IPCC Fourth Assessment report, numerous simulations available from a broad range of climate models, run for various future emission scenarios, were used to assess climate change projections. Taken together with information from observations, these provide a quantitative basis for estimating likelihoods for many aspects of future climate change. The best-estimate projections from models indicate that decadal average warming over each inhabited continent by 2030 is insensitive to the choice among SRES scenarios and is *very likely* to be at twice as large (about 0.2˚C per decade) as the corresponding model-estimated natural variability during the 20th century. Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would *very likely* be larger than those observed during the 20th century. Projected global average surface air warming for 2090–2099 relative to 1980–1999, under SRES emissions marker scenarios, range from a best estimate of 1.8˚C (*likely* range 1.1˚C to 2.9˚C) for the low scenario (B1) to 4.0˚C (*likely* range 2.4˚C to 6.4˚C) for the high scenario (A1FI), with a best estimate of 2.8˚C (likely range 1.7˚C to 4.4˚C) for the moderate scenario A1B (IPCC, 2007a).

Geographical patterns of projected surface air temperature warming are scenario independent, with greatest temperature increases over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean, consistent with the observed changes during the latter part of 20th century, as described in Chapter 2.

Table D1 provides detailed regional information for the likely changes in climate between the 1980 to 1999 period and the 2080 to 2099 period from a set of 21 global models in the multi-model data set for the A1B scenario. The temperature changes are given as the relative warming to the global annual mean warming. It is evident that all land regions are very likely to warm during the 21st century. In particular, warming in all of Africa is very likely to be greater than the global annual mean warming in all seasons, and drier subtropical regions warming more than the moister tropics. In Saharan Africa and the Mediterranean region, the warming is likely to be the largest in summer, with highest summer temperature likely to increase more than average summer temperatures. The warming is likely to be well above the global mean in Central Asia, the Tibetan Plateau, and North Asia; above the global mean in South Asia; and similar to the global mean in South East Asia. It is very likely that summer heat waves/hot spells in East Asia will be of longer duration, more intense, and more frequent. It is also very likely that there will be fewer very cold days in East Asia and South Asia. In Central and South America, the warming is likely to be similar to the global mean warming in southern South America but larger than the global mean warming in the rest of Central and South America through all seasons. Compared to the land regions, the warming in ocean areas and small islands is somewhat smaller. The warming in the Caribbean, Indian Ocean, and North and South Pacific islands is very likely to be smaller than the global annual mean warming in all seasons (IPCC, 2007a, Chapters 10, 11).

Table D1. Model Consistency in Regional Relative Changes in Temperature and Precipitation Projections in the Multi-Model Ensembles for A1B Scenario for 2080–2099 with Reference Period 1980–1999

Region		Temperature			Precipitation		
		DJF	JJA	Annual	DJF	JJA	Annual
AFRICA	**WAF** (12S,20W to 22N, 18E)	++	++	++	i	i	i
	EAF (12S,22E to 18N,52E)	++	++	++	+	i	+
	SAF (35S,10E to 12S,52E)	++	++	++	0	– –	i
	SAH (18N,20E to 30N,65E)	++	+++	++	–	i	i
EUROPE	**NEU** (48N,10W to 75N,40E)	+++	+	++	+	i	+
	SEM (30N,10W to 48N,40E)	+	+++	++	–	– –	–
ASIA	**NAS** (50N,40E to 70N,180E)	+++	++	+++	++	+	+
	CAS (30N,40E to 50N,75E)	++	+++	++	i	–	i
	TIB (30N,50E to 75N,100E)	+++	+++	++	+	i	+
	EAS (20N,100E to 50N,145E)	++	++	++	+	+	+
	SAS (5N,64E to 50N,100E)	++	+	++	i	+	+
	SEA (11S,95E to 20N,115E)	+	+	+	+	+	+
NORTH AMERICA	**ALA** (60N,170W to 72N,103W)	+++	+	+++	++	+	++
	CGI (50N,103W to 85N,10W)	+++	+	+++	++	+	+
	WNA (30N,50E to 75N,100E)	++	++	++	+	i	i
	CNA (30N,103W to 50N,85W)	++	+++	++	i	i	i
	ENA (25N,85W to 50N,50W)	++	++	++	+	i	+
CENTRAL AND SOUTH AMERICA	**CAM** (10N,116W to 30N,83W)	+	++	++	–	–	–
	AMZ (20S,82W to 12N,34W)	++	++	++	i	i	i
	SSA (56S,76W to 20S,40W)	+	+	+	i	i	0
ASTRALIA AND NEW ZEALAND	**NAU** (30S,110E to 11S,155E)	++	++	++	i	i	i
	SAU (45S,110E to 30S,155E)	+	+	+	i	–	i
POLAR REGIONS	**ARC** (60N,180E to 90N,180W)	+++	+	+++	++	+	+
	ANT (90S,180E to 60S,180W)	+	+	+	+	+	+
SMALL ISLANDS	**CAR** (10N,85W to 25N,60W)	+	+	+	i	– –	–
	IND (35S,50E to 17.5N,100E)	+	+	+	0	0	0
	MED (30N,5W to 45N,35E)	+	+	+	–	– –	–
	TNE (0,30W to 40N,10W)	+	+	+	i	i	0
	NPA (0,150E to 40N,120W)	+	+	+	0	+	+
	SPA (55S,150E to 0,80W)	+	+	+	0	0	0

Classification	Temperature		Precipitation	
	+++	Much greater than average warming	++	Large increase
	++	Greater than average warming	+	Small increase
	+	Less then average warming	0	No change
	i	Inconsistent magnitude of warming	–	Small decrease
	–	Cooling	– –	Large decrease
			i	Inconsistent sign

Source: The table is established based on IPCC, 2007a, Chapter 11, table 11.1, which listed the distributions of regional averages of temperature and precipitation projections from a set of 21 global models in the multi-model data set for the A1B scenario.

Note: For temperature changes, regions are classified as showing either agreement on warming in excess of 40 percent above the global annual mean warming ("Much greater than average warming"), agreement on warming greater than the global annual average ("Greater than average warming"), agreement on warming less than the global annual average ("Less than average warming"), or disagreement among models on the magnitude on regional relative warming ("Inconsistent magnitude of warming"). There is also a category for agreement on cooling (which never occurs). A consistent warming with median (50 percent) quartile values among 21 models fulfilling the best estimate and the middle half (25–75 percent) of quartile distribution falling in the likely range in the classified category is deemed necessary for agreement. The best estimate and the likely range of global annual average warming for A1B is 2.8°C and 1.7–4.4°C, and therefore a regional 40 percent amplification represents warming of 3.9°C and range

(continued)

Table D1 (continued)

of 2.4–6.2°C. For precipitation changes, classifications are as showing either agreement on increase with an average change of greater than 20 percent (“Large increase”), agreement on increase with an average change between 5 percent and 20 percent (“Small increase”), agreement on a change between −5 and +5 percent or agreement with an average change between −5 and +5 percent (“No change”), agreement on decrease with an average change between −5 and −20 percent (“Small decrease”), agreement with an average change of less than −20 percent (“Large decrease”), or disagreement (“Inconsistent sign”). A consistent result for a region in which not only the median (50 percent) quartile value falls in the classified range, but also the middle half (25–75 percent) of the quartile distribution is all of the same sign in the precipitation response is deemed necessary for agreement. The only exception is the category “No change,” for which agreement is also defined as the middle half (25–75 percent) of the distribution between −5 and +5 percent. The regions are defined by rectangular latitude/longitude boxes, and the coordinates of the bottom left-hand and top right-hand corners of these are given in degrees in the first column under the region acronym (see table notes for full names of regions). Information is provided for land areas contained in the boxes except for the Small Islands regions, where sea areas are used, and for Antarctica, where both land and sea areas are used.

Regions are: West Africa (WAF), East Africa (EAF), South Africa (SAF), Sahara (SAH), Northern Europe (NEU), Southern Europe and Mediterranean (SEM), Northern Asia (NAS), Central Asia (CAS), Tibetan Plateau (TIB), East Asia (EAS), South Asia (SAS), Southeast Asia (SEA), Alaska (ALA), East Canada, Greenland and Iceland (CGI), Western North America (WNA), Central North America (CNA), Eastern North America (ENA), Central America (CAM), Amazonia (AMZ), Southern South America (SSA), North Australia (NAU), South Australia (SAU), Arctic (ARC), Antarctic (ANT), Caribbean (CAR), Indian Ocean (IND), Mediterranean Basin (MED), Tropical Northeast Atlantic (TNE), North Pacific Ocean (NPA), and South Pacific Ocean (SPA).

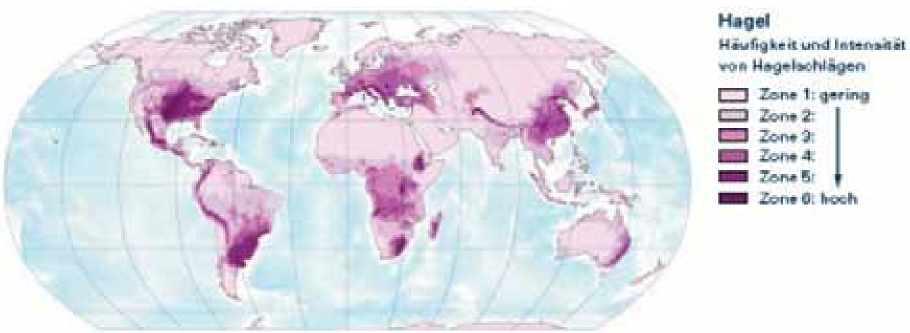
Appendix E. Icing and Hail

There are several other meteorological effects that impact the energy sector. For instance, Bonelli and Lacavalla (2010) investigated the effect of icing on power lines using proxy meteorological data for a few sites in Italy: although their results show some evident local climatic trends, further analysis and more accurate observations are needed to corroborate these findings. Apart from this study, several other authors have investigated the process of icing on power lines (Fikke et al. 2007; Leblond et al. 2006; Makkonen, 1998). However, given their very localized nature, it is difficult to assess icing hotspots on a large scale.

Another example is the effect of hail on solar panels: according to General Electric,[1] the current PV materials can withstand 125-mph (200-kph) winds and 2.5-cm hailstones at 80.5 kph. A map of observed hailstorm frequency is shown in Figure E1. A few studies have looked at possible changes in hailstone events under climate change but no general trend has been discerned. For instance, while Botzen et al. (2010) found a 25 to 50 percent increase in hail storm damage in the Netherlands associated with a 2°C temperature increase, no significant change in hail storm risk for Australia was detected for similar conditions (Niall and Walsh, 2005).

Given their relatively small scale, these are phenomena that require specialized monitoring and assessment, often beyond what is achievable even with current observational networks and numerical weather prediction resolution models, re-analyses, or climate models. In such instances, tools such as meso-scale or micro-scale models can, and are, used (for example, Musilek et al., 2009).

Figure E1. World Map of Hail Frequency and Intensity



Source: Munich Re, 2009.
Notes: Zone 1: low, zone 6: high.

Notes

1. http://www.gepower.com/prod_serv/products/solar/en/faqs/resid_sys.htm.

Appendix F. Electric Utilities Adapt Their Practices to Respond to Natural Disasters

Electric utilities are adapting their practices to respond to natural disasters. This Annex discusses Mexico's Electricity Utility Plan for the Attention to Natural Disasters.

Background. Mexico is located inside the Pacific Rim of Fire and in the intersection of several tectonic plates, increasing its risks for destructive earthquakes. The country's Pacific and Gulf coasts are also vulnerable to tropical storms, cyclones, and hurricanes. Climate change is increasing the frequency and intensity of hurricanes in the coastal areas, constantly affecting the distribution infrastructure of the electric utility and interrupting electricity service to thousands of customers.

The national electricity utility, CFE, generates, transmits, and distributes electricity in the whole Mexican territory. As of July 2010, the electricity system's total installed generation capacity is 51,121 MW. The electricity network is comprised of 49,252 Km of transmission lines (400 to 150 KV), 46,973 km of sub-transmission lines (138 to 69 KV), and 647,047 Km of distribution lines (34.5 to 2.4 KV). The company serves 33.9 million customer accounts. Except for medium and large industries, most of the customers receive their electricity supply from distribution lines. To manage and attend to customers in different regions in the country, the utility's distribution business is organized into 10 distribution regions with their own management.

Distribution infrastructure is especially vulnerable to natural disasters, such as hurricanes, tropical storms, floods, and earthquakes. High winds from storms can tear down poles and transformers, leaving tens of thousands of customers without electricity service. Quickly restoring electricity services after faults is a priority to any utility. Restoration becomes even more important during natural disasters, as electricity services become also crucial to support relief efforts.

Though the utility has introduced some minor changes to distribution facilities' construction codes, the utility has focused on the effort to improve restoration times after natural disasters. These minor changes include improving foundations of the line's poles and improved anchoring of transformers and conductors to poles. These cost-effective changes have improved the chances of distribution lines remaining in service during storms. However, according to the Mexican and other electric utilities, it would be impossible or cost-prohibitive to build distribution infrastructure that can withstand major disasters such as tsunamis or higher-level hurricanes. For this reason, the focus of the CFE has been on improving service restoration after disasters through a careful implementation of emergency plans.

The CFE has implemented a Plan for Attention to Natural Disasters. The objective of the plan is to define the activities and control mechanisms that should be followed to effectively deploy the material and human resources necessary to restore electricity service after natural disasters. Making materials and human resources available has proven to be crucial to speed up restoration times. The plan, adopted in 2006, has been a key instrument and has considerably improved the utility's response to natural disasters.

One of the activities considered in the plan is the establishment and management of national and regional emergency stock facilities for electrical equipment. With budget determined by the plan, these facilities permanently contain electrical equipment that can be used exclusively for restoration works after natural disasters. The equipment includes transformers, wire, fuses, breakers, and other materials used for the construction of distribution lines. These resources, along with other material and human resources available to the areas affected by disasters, are used in a carefully designed process to speed up restoration efforts. The process is divided into three stages, namely, before, during, and after the disaster.

CFE's Meteorology Center continuously monitors the evolution of different phenomena such as tropical storms. If the MC finds that a particular storm may become a threat to the utility's infrastructure, a Strategic Operation Center convenes. The Strategic Operation Center is a virtual gathering of all managers and superintendents of the areas that could potentially be affected by the storm. If the Meteorology Center concludes that the storm trajectory and intensity is such that it has become an imminent threat to particular distribution infrastructure of certain regions of the utility, the Strategic Operation Center emits an official declaration of *preventive natural disaster state*. This official declaration gives managers of the potentially affected distribution regions the green light to initiate preparatory works for service restoration. These preparatory works include calling for material from the emergency regional stock facilities as well as displacing crews to the potentially affected areas before the storm arrives. Depending on the expected severity of the storm, regional managers can also deploy additional private construction crews, which they can hire using expedited procurement rules. In addition, once the declaration of preventive natural disaster is released to particular regions, a National Support Committee convenes. The National Support Committee is formed of managers and superintendents of the regions that neighbor the potentially affected areas. This constitutes the preventive phase, whose main objective is deploying equipment and human resources before the storm strikes. Roads flooded or blocked by debris tend to be a major obstacle to quickly deploy reconstruction crews and their equipment.

During the disaster, crews can start to perform restoration works. When performing these works, crews follow specific emergency construction and safety rules. If the intensity of the disaster requires it, managers of the affected region can call upon the National Support Committee to bring more crews from other distribution regions and material from the national stock rooms. Depending on local market conditions, managers can also opt to purchase materials and hire additional construction services from third parties using the expedited procurement rules. The objective of this stage is to ensure that affected regions have all the support from neighboring distribution regions. At the same time it ensures that managers from affected regions have the right tools to speed up restoration efforts.

During the disaster, affected regions need to comply with a series of control mechanisms to ensure that the plan is implemented in accordance with its governing and administrative procedures. Since CFE insures its entire infrastructure, during the event the utility starts to assemble all required documentation to process insurance claims. The emergency plan has been instrumental to expedite the claims with insurance companies. After the disaster, regional managers need to report the results of the application of the plan and can propose any improvement. Managers of affected regions are responsible for keeping track and ensuring all of the processes have been met during the emergency.

The implementation of the Plan for the Attention to Natural Disasters has greatly improved the company's response to natural disasters. Distribution zones more frequently affected by hurricanes (for example, the Pacific region, the Gulf of Mexico, the Yucatan Peninsula, and the northeast) have greatly improved their restoration time after major storms. It used to take several weeks before electricity services could be restored to all customers. With the implementation of the plan, restoration times have been reduced to a number of days. Although the distribution segment is more frequently affected by natural disasters, the plan also deals with impacts in the generation and transmission segments.

Appendix G. Locally Tailored Adaptation Options: An Example

In the coming decades, Albania is projected to face rising average temperatures, increasing risk of heat waves, intense precipitation events, decreased annual average precipitation, as well as rising sea levels. Albania's First National Communication to the UNFCCC (2002) highlighted some key vulnerabilities of the energy sector, including effects on energy demand for space heating, space cooling, water heating, and refrigeration. It estimated that rising temperatures could lead to a 12 to 16 percent reduction in energy demand for space heating in the residential sector by 2025, compared to the 1990 baseline (Albanian Ministry of Environment, 2002).

In contrast, demand for cooling is projected to increase in hotter summers. But energy demand drivers are not limited to temperature, with precipitation, wind speed, and cloud cover also being important factors. Since over 90 percent of Albania's domestic electricity is generated by hydropower facilities, it is particularly vulnerable to projected decreases in precipitation. To build greater understanding of potential risks and management options, the World Bank, together with the government of Albania, conducted a series of workshops in Tirana in 2009 on climate risks and vulnerabilities in the country's energy sector as well as opportunities presented by climate change. Participants included a cross section of stakeholders from the government, key agencies and institutions, academia, the private sector, and civil society. They concluded that there are several critical actions that Albania could take now to support optimal use of energy, water resources, and operation of hydropower plants. Five critical actions are as follows:

1. **Improve the way that institutions monitor, forecast, and disseminate information** on meteorological and hydro-meteorological conditions. Albania could develop (in-country) or obtain (from elsewhere) weather and climate forecasts appropriate for energy sector planning, to cover short-range forecasts (1–3 days), medium-range forecasts (3–10 days), seasonal forecasts, and regional downscaled climate change projections. This information could support energy sector stakeholders to undertake joint climate risk assessments across shared water resources and regional energy networks**.**
2. **Improve energy efficiency** by encouraging and helping end users to manage their demand for power. There are enormous opportunities for Albania to close its supply–demand gap through improved energy efficiency and demand-side management. The large technical and commercial losses in the distribution system could be reduced and demand-side management could be improved through, for example, the improved bill collection and establishment of cost-recovery tariffs (amending energy subsidies that are distorting market signals).
3. **Diversify energy supply, domestically and through trade.** Climate change emphasizes the imperative for Albania to increase the diversity of its energy supplies—both through increased regional energy trade and through developing a more diverse portfolio of domestic generation assets, ensuring that these are designed to be resilient to climate change. The active scenario laid out in the draft National Energy Strategy aims to improve energy security by encouraging development of renewable energy generation assets (solar, small hydropower plants, wind, and biomass) and thermal power plants.

4. **Ensure that the management and development of water resources integrates all sectors**—energy, agriculture, water supply and sanitation, and cross-border concerns—along with environmental and social concerns.
5. **Build climate resilience into all new investments.** Albania is on the brink of a significant adaptation opportunity. With major investments in upgrading, new energy assets on the horizon, and the privatization of assets, the earlier the climate risks are considered, the greater the opportunities to identify and implement solutions that will make the energy system more robust and resilient for coming decades.

Table G1 provides a more detailed summary of options identified in 2009 through a series of technical meetings with local stakeholders that discussed the vulnerabilities and risks posed to Albania's energy security as a result of climate change (to 2050).

Table G1. Options to Improve the Climate Resilience of Albania's Energy Sector

Next steps **Actions marked with an asterisk (*) are *no-regret* actions that could improve Albania's energy security even without climate change. Those marked with a cross (†) are included in the draft National Energy Strategy *active* scenario.**
Informational
* Compile digital databases on historic and observed climatological and hydrological conditions. Provide free access on the Web to these data.
* Improve coordination of Albania's forecasting agencies (the Military Weather Services, Institute of Energy, Water and Environment and the National Air Traffic Agency), by sharing data, expertise, and financial strength to support better-quality forecasting. These organizations could collectively engage with energy sector stakeholders to understand their data needs to support management of the energy/climate interface.
* Upgrade Albania's weather and hydrological monitoring network, focusing most urgently on the Drin basin: Monitoring sites could be equipped with automatic devices able to record and transmit in real time the key weather variables (rainfall, runoff, temperature, sunshine hours, wind speed, reservoir head, evaporation, turbidity, water equivalent of snow). • Measure sedimentation in reservoirs, which has not been measured for 40 years. • The data above could be collected by the Albanian Electricity Corporation (KESH) and used in managing reservoirs for safety and energy production. • Wind data are also required, measured at the height of wind turbines (80 to 100 m), to ensure wind farms are designed appropriately and will operate efficiently. Once these data are available, explore whether high wind speeds coincide with periods of lower rainfall, in which case wind power could provide a useful resource when generation from hydropower facilities is lower.
* Develop in-country or obtain weather and climate forecasts appropriate for energy sector planning needs: • Short-range forecasts (1 to 3 days ahead) could be provided by the Institute of Energy, Water and Environment—including weather products for energy demand forecasting (temperature, cloudiness), reservoir management (rainfall), and safety and disaster management (heavy rainfall, high winds, lightning strikes). • *Medium-range forecasts (3 to 10 days ahead) could be obtained by subscribing, for example, to the European * Centre for Medium-range Weather Forecasting regional forecasts—particularly for use by KESH—to facilitate effective management of water reserves for hydropower generation. • *Seasonal forecasts (several months ahead) could be developed by the Institute of Energy, Water and Environment from statistical models of teleconnections, using observed and historical data for application to energy sector planning. • Climate change scenarios (years and decades ahead): ◦ These should be at a spatial resolution suitable for river basin planning (for example, 50 km × 50 km). ◦ They should be developed by downscaling ensembles of outputs from GCMs, which are provided by Met Agencies around the world, coordinated through the World Meteorological Organization. ◦ The GCMs to be included in the ensemble should be those that are best able to simulate the observed (historic) precipitation. * Consider providing free access to these data to energy sector stakeholders. Short-range and medium-range forecasts should be available in real time via the Web.

(continued)

Next steps **Actions marked with an asterisk (*) are *no-regret* actions that could improve Albania's energy security even without climate change. Those marked with a cross (†) are included in the draft National Energy Strategy *active* scenario.**
Undertake further research on climate change impacts using downscaled climate change scenarios, researching the impacts of changes in seasonal conditions and extreme climatic events.
* Update watershed models and maps of Albania's climate to support planning for optimization of future hydropower assets.
* Join networks of experts working on climate and climate change issues, for instance, WMO, EUMetNet, and EUMetNet Composite Observing System.
* Create partnerships between weather, climate, hydrological experts, and energy sector stakeholders to enhance dissemination of information and to ensure that data providers understand user needs.
* Strengthen regional cooperation on sharing of weather/climate information and forecasting and undertake research to develop shared understanding of region-wide climate change risks and their implications for energy security, energy prices, and trade, including: • Data exchange on historical and recent observed data • Joint studies and monitoring activities with institutions in neighboring countries, especially in the two upper watersheds of the Drin and in the Vjosa watershed • Regional studies to establish whether all South East Europe's watersheds are positively correlated (that is, whether they experience wet or dry years or seasons at the same time, and whether wet and dry years correspond with cold and hot years): ◦ If so, the existing and proposed hydropower assets in the region may be exacerbating the region's vulnerability to climate risks. ◦ If not, it may be possible to undertake an investment strategy to diversify risk across the region.
* Work with regional partners to develop better knowledge of the linkages between energy prices and hydrological conditions in the face of climate change: • Marginal costs of energy production are higher in dry years than wet years. • Some data linking these factors are available for 2010 and 2015. • Research should be undertaken to develop data out to 2020 and 2030, taking account of climate change projections.
* Improve understanding of current rates of coastal erosion and of the impacts of rising sea levels and storm surges on future erosion rates, for better management of coastal assets (for example, TPP and port facilities).
* Learn from experience of energy sector experts worldwide on managing current and future climate-related risks (for example, hydropower experts in Brazil and EDF in France, both of which have been researching these issues for some time).
* Monitor changing ground conditions and concentrations of pollutants at Patos Marinza.
Identify whether contaminated land remediation at Patos Marinza would be effective/quick enough in the light of climate change impacts and, if not, develop additional management plans while rehabilitation is under way.
* Monitor potential for pollution incidents at coal mines due to heavy downpours.
***Institutional*: Managing current climatic variability and changes in average climatic conditions**
* Improve and exploit data on reservoir use, margins, and changes in rainfall and runoff to improve management of existing reservoirs.
*† Consider providing incentives for energy efficiency measures to reduce demand.
* Support enforcement of measures to reduce technical and commercial losses of water.
* Work with water users in the agricultural sector to devise agreed strategies for managing shared water resources with owners of hydropower plants. This could draw on the outcomes of World Bank research investigating climate change impacts on agriculture in Albania. The outcomes of the research presented in this report and the agricultural assessments could be integrated to consider the cross-sectoral issues around water management.
*† Support enforcement of measures to reduce commercial losses from the power distribution system.

(continued)

Next steps **Actions marked with an asterisk (*) are *no-regret* actions that could improve Albania's energy security even without climate change. Those marked with a cross (†) are included in the draft National Energy Strategy *active* scenario.**
Incorporate robustness to climatic variability and climate change in regulations, design codes, energy-sector proposals, site-selection decisions, environmental impact assessments, contracts, public−private partnerships for new energy assets, and other policy instruments for new facilities.
Ensure that proposed locations for new large hydropower plant (LHPP) will be sustainable in the face of climate change risks.
Assess use of tariffs and incentives to promote climate resilience of energy assets.
Consider amendment to regulations to capture climate change costs in energy prices and the price of water.
* Strengthen measures to control illegal logging that contributes to soil erosion and siltation of reservoirs.
Set up a committee to provide oversight and monitoring of progress on climate change adaptation.
***Institutional*: Managing climatic extremes**
Review and upgrade emergency contingency plans for LHPPs, to take account of expected increases in precipitation intensity due to climate change, ensuring that they include: monitoring of precipitation, modeling of river flows, communication instruments and protocols for downstream communities, and plans for evacuation.
* Consider use of Power Purchase Agreements with neighboring countries and large energy users to assist Albania in coping with the impacts of extreme droughts on energy security. This would need to be supported by real-time data on regional runoff and precipitation (as outlined above), and could include: • Off-take arrangements with countries generating energy through less climatically vulnerable assets such as thermal power plants • Power swap agreements, whereby Albania could buy thermal energy from neighbors at low cost during off-peak hours at night while allowing its reservoirs to fill, then recoup the energy during the next day's peak load hours via a higher fall • Instituting formal arrangements with large energy users such that they agree to their electricity supply being cut off in an extreme situation, in return for which they pay less for electricity
* Investigate applicability of weather coverage and insurance instruments for energy sector risk management.
* Support development of contingency plans in collaboration with stakeholders for better management of extreme climatic events and ensure that resources could be mobilized effectively to respond to them.
* Ensure that regulations on dam security are enforced.
Physical/technical
Optimize existing energy assets: • * Improve maintenance of existing assets, many of which were designed and constructed several decades ago. • Check that the sizing of existing assets is robust to climate variability and projected changes in average climatic conditions and explore whether water storage could be increased at reasonable cost to help manage seasonal variations. • Review old and/or inefficient equipment and identify cost-effective measures to improve efficiencies, such as: ◦ Clearing /redesigning trash racks ◦ Upgrading turbines and generators ◦ Replacing equipment to reduce water losses (for example, shut-off valves) ◦ Improving aprons below dams to reduce erosion ◦ Raising dam crest on Fierze ◦ Increasing capacity of spillways on Fierze and Komani dams ◦ Developing pump storage scheme on Drin River cascade ◦ Digging wider channels for SHPPs
* Reduce losses: • Reduce electricity transmission losses. • Reduce losses of water—hold dialogues with stakeholders sharing watersheds to discuss losses and establish how best to work together to reduce them. • † Improve demand-side energy efficiency through incentives (for example, for insulation and energy-efficient appliances) and enforcement.

(continued)

Next steps **Actions marked with an asterisk (*) are *no-regret* actions that could improve Albania's energy security even without climate change. Those marked with a cross (†) are included in the draft National Energy Strategy *active* scenario.**
Ensure new assets are resilient: • For new assets at the design stage, review the robustness of design and site locations to climatic variability and projected climate change—including design of energy-generation assets as well as associated infrastructure, such as port facilities.
*† Diversify energy-generation asset types into nonhydropower renewables and thermal power plants, ensuring that site selection and design are resilient to climate change.
† Increase hydropower installed capacity, ensuring that new facilities are designed to cope with changing climate risks.
*† Provide better interconnections to facilitate regional energy trade.
*† Reduce energy demand and improve energy efficiency through greater use of domestic solar water heating, improved building standards, use of lower energy appliances, and use of alternative heating sources other than electricity.
Optimize transmission and distribution by reducing technical losses (for example, insulation of cables, undergrounding of critical cables, consider DC rather than AC for long lines).
*† Install alternative fuel sources (other than electricity) for heating buildings, such as solar water heaters, geothermal.

Source: Extract, World Bank, 2009e.

Table AG2 summarizes the highest-priority weather information needs and availability.

Table G2. Weather and Climate Information for Energy Sector Management in Albania

	Design		Operations and Maintenance	
	Current Resources	Options to Improve	Current Resources	Options to Improve
Large Hydropower Plants (LHPP)	For LHPP design, hydrological models and time series of flow are needed, but they are out of date	Revise hydrological models, recommence measurements; digitize all available data	For continuous optimization of reservoir levels, continuous awareness of water in the system and rain entering the system is needed There is only a small network of river-level gauges in the Drin watershed Radar assessments of ongoing precipitation would be very useful; precipitation forecasts would be helpful, but there is no radar, and numerical precipitation forecasts are low resolution and not verified	Expand river-level gauge network in Drin; initiate in Mati; and add rain gauges in both watersheds to indicate water entering the system (radar better) Identify best-skilled atmospheric models with respect to historical Albanian precipitation data Downscale an ensemble of such to facilitate analysis of watersheds under climate change

(continued)

	Design		Operations and Maintenance	
	Current Resources	**Options to Improve**	**Current Resources**	**Options to Improve**
Small Hydropower Plants (SHPP)	For design of new SHPPs or to select which concessions are economically promising today, watershed models are needed, but those available date to 1990 or before, and rainfall statistics to 1990	Undertake revision of hydrological models Digitize rainfall data and make data publicly available Improve monitoring	To plan power generation and turbine management, operators have only low-resolution precipitation forecasts for the very near term Forecasts are not routinely verified	Highly resolved precipitation forecasts could be undertaken and could provide probabilistic information out to seven days Rain gauges would indicate water entering the system (radar better); not only for LHPPs but also for SHPPs would be useful to identify best-skilled atmospheric models with respect to historical Albanian precipitation data (and downscale an ensemble to facilitate analysis of watersheds under climate change)
Power Transmission and Distribution (T&D)	To devise distribution network protected against severe weather, climate data are needed, but what exists is old and much is not digitized	Digitize the climate data and make data available publicly; strengthen monitoring	To anticipate risks to network and undertake rapid repairs, storm forecasts and lightning detection are needed, but severe storms are not reliably forecast; no lightning detection network in place; no radar	Initiate highly resolved probabilistic weather forecasts with verification to tune accuracy; initiate lightning detection to speed network repairs; undertake weather and radar monitoring to assess storms under way
Thermal Power Plants (TPP)	To assess availability of cooling water for river- or lake-cooled TPPs, water temperatures, ambient air temperatures, and climate data are needed Data up to 1990 are available; beyond that data sets are incomplete and hydrological models are old	Revise hydrological models to show availability of cooling water; expand monitoring of rainfall to support ongoing revisions	To assess adequacy and temperature of cooling water and ambient air temperatures, assessment of stream levels and rainfall entering the system is needed, but lacking No radar Forecasts needed but these are low resolution and risky to use, as they do not provide probabilistic information and are not verified	Monitor rainfall entering the system to provide cooling water (radar, rainfall, stream levels); improve resolution of weather forecasts and provide probabilistic information

(continued)

	Design		Operations and Maintenance	
	Current Resources	**Options to Improve**	**Current Resources**	**Options to Improve**
Wind	To site and design wind-generation plants, knowledge of wind speed distributions at turbine height is needed, but few data are available Maps have been undertaken at low resolution, but their accuracy at turbine height is not known; data at turbine height have been taken in a few places but they are not long term	Improve resolution of wind maps; add monitoring of wind at turbine height	To anticipate wind extremes and assure security of infrastructure, wind forecasts are needed, but forecasts are at very low resolution, lack probabilistic information, and are not verified	Improve resolution of forecasts; add monitoring of wind at key altitudes; calibrate the forecasts
Solar	To site large solar arrays, need data on irradiance and cloudiness Satellite imagery could be used Future cloudiness is not known but is generally projected by climate models to decrease in summer associated with decrease in precipitation; this is a skill gap in climate modeling	Climatology of cloudiness assessed in more detail; assessment of model accuracy	To anticipate solar power generation, cloudiness forecasts are needed, but these are available at low resolution and are not verified	Increase resolution of forecasts, include cloudiness in further detail
Energy Demand	To forecast demand long term, KESH has data on demand patterns in the past	The widest possible range of climate projections covering natural effects as well as anthropogenic effects should be reviewed to understand the range of future demand possibilities linked to temperatures, cloudiness, etc.	To forecast demand day to day, forecasts of key demand variables (such as temperature, cloudiness) are needed, but these are available only at low resolution, without probabilistic information, and are not verified	Increase resolution of forecasts, provide probabilistic information, undertake verification and tuning

Source: Hancock and Ebinger, 2009.

Appendix H. Adapting to Climate Change on Mexico's Gulf Coast

This annex discusses projected climate change on Mexico's Gulf Coast. It explores the potential impacts on the oil and gas industry, and adaptation measures. The annex draws on available published literature.

Mexico's Oil and Gas Industry

Ninety seven percent of Mexico's primary energy production of about 251 million tons of oil equivalent (Mtoe) in 2008 was from hydrocarbons; the remainder was provided through renewable energy sources.[1] Hydrocarbon production is dominated by crude oil (156 Mtoe) and natural gas (65.5 Mtoe), with 81 percent of domestic oil production originating in fields located on the Gulf Coast (Figure H1). Although Mexico was ranked as the 15th largest natural gas producer globally in 2008 (Pemex, 2010), domestic gas production has been declining and Mexico is today a net importer of gas.

Two of six refining complexes are located on the Gulf Coast and the largest (Cadereita) is on the coastal plains (Figure H2). There are 5,200 km of oil pipelines and 9,000 km of pipelines carrying by-products, most of which originate in the Gulf of Mexico. Pipeline and transport infrastructure is relatively old, with significant fugitive emissions of volatile organic compounds. Nearly 80 percent of methane emissions from natural gas are from wet seals used with the operation of compressors used in the production, storage, and distribution network.

As of 2007, the total installed capacity of the electric power system, including self-generation and export projects, was about 60 GW, generating about 260 TWh and using about 51.4 Mtoe annually. About 60 percent of power generation and 76 percent of nominal generation capacity is fossil-fuel based. Diesel and fuel oil use in the power sector is

Figure H1. Exploration and Production Sites in Mexico

Source: PEMEX, 2008.

Figure H2. Oil Refineries, Distribution Terminals, and Pipelines in Mexico

Source: PEMEX, 2008.

progressively being replaced with natural gas and renewable energy. There is also potential to displace generators driven by fuel oil, diesel, or gas turbine with wind power at a number of locations: Sierras De La Rumorosa and San Pedro Martir (274 MW), Yucatán (352 MW), and the Riviera Maya (157 MW) (SENER and GTZ, 2006).

According to its Third National Communication to the UNFCCC, Mexico emitted 643 million tons of carbon dioxide equivalent[2] (Mt CO_2e) in 2002, of which almost 400 Mt CO_2e came from the combustion of fossil fuels. Mexico's CO_2 emissions have been growing steadily over the past 25 years.[3] The oil and gas sector is responsible for about 12 percent of the GHG emissions, about half of which are classified under energy generation.

Future Climate

Mexico is particularly vulnerable to the impacts of climate change (SEMARNAP, 1997, 2007, and 2009; IPCC, 2007b; PECC, 2009), many of which may be irreversible. Impacts include an increase in sea surface temperature in the Gulf of Mexico, continuous sea level rise affecting coastal areas and inland basins, intensification of hurricanes, changes in the hydrological cycle (with an increase in heavy rains and storms, longer and more frequent drought episodes), and net decreases in water runoff, among others.

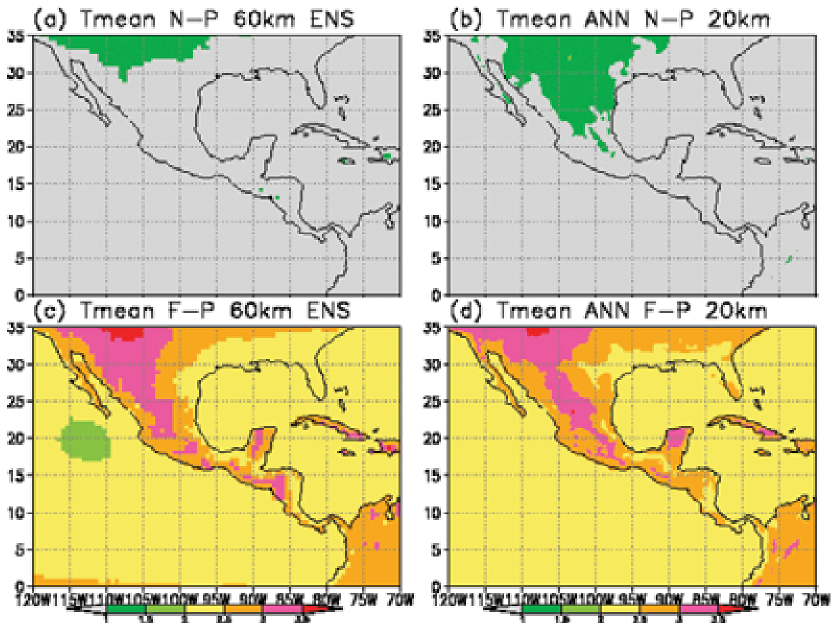
A high-resolution projection of climate has been completed to the year 2100 using the Earth Simulator[4] for the country as a whole and for the Gulf of Mexico region. The IPCC scenario used in this study was A1B,[5] which projects a temperature increase of between 1.3 and 3.5 degrees Celsius by 2100. The analysis was conducted primarily to assess temperature and rainfall anomalies and extreme events. Results on rainfall, moisture, and evaporation are also reported and later compared with other model outputs. The simulations were performed at a grid size of about 20 km and routinely compared with 60-km mesh ensemble runs to ascertain robustness. A detailed description of the model and its performance in the 10-year present-day simulation with sea surface temperature can be found in Mizuta et al. (2006).

Climate was projected over Mexico to mid-century (2035–2049) and to the end of the 21st century (2075–2099). These projections were compared with the present (1979–2003). The projections cover 95 parameters, including temperature, rainfall, soil moisture, and sea level rise anomalies as well as extreme events. The projections also include estimates of the frequency of coastal storms. Some select results are discussed next.

Temperature. The high spatial resolution (20-km grid size) of the projections makes it possible to examine changes in temperature taking account of the complex topography that exists in Mexico.[6] As the computing time requirements for a high-resolution model are demanding, the runs for Mexico at a high resolution were compared with an ensemble of results for a medium-scale grid (60 x 60 Km). The projection indicates a temperature anomaly consistent with global projections, with higher deviations in the mountain areas and in the Yucatan region. (See Figure H3.)

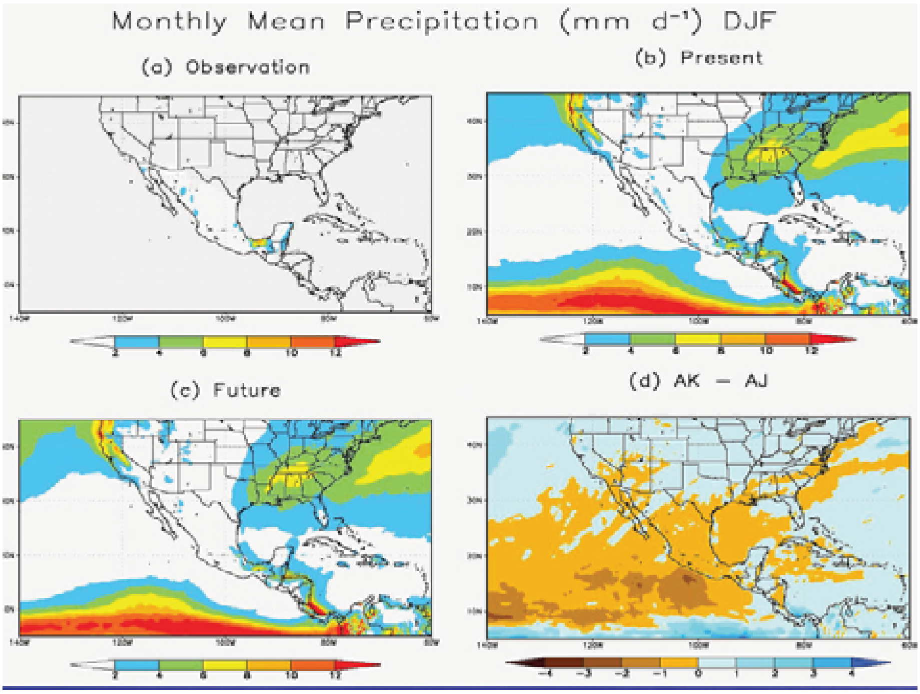
Precipitation. Of particular concern is the effect of global warming on annual precipitation in Mexico. *At a national scale, Mexico is already confronting serious water management challenges and facing a threat of droughts.* Demand for water continues to grow and in some areas it has already become a bottleneck for economic activity, limiting growth

Figure H3. Projection of Temperature Anomalies under Scenario A1B for the End of the Century



Source: Figure generated under the Memorandum of Understanding (MOU) between MRI and the World Bank.

Figure H4. Observed and Projected Precipitation Patterns for Mexico



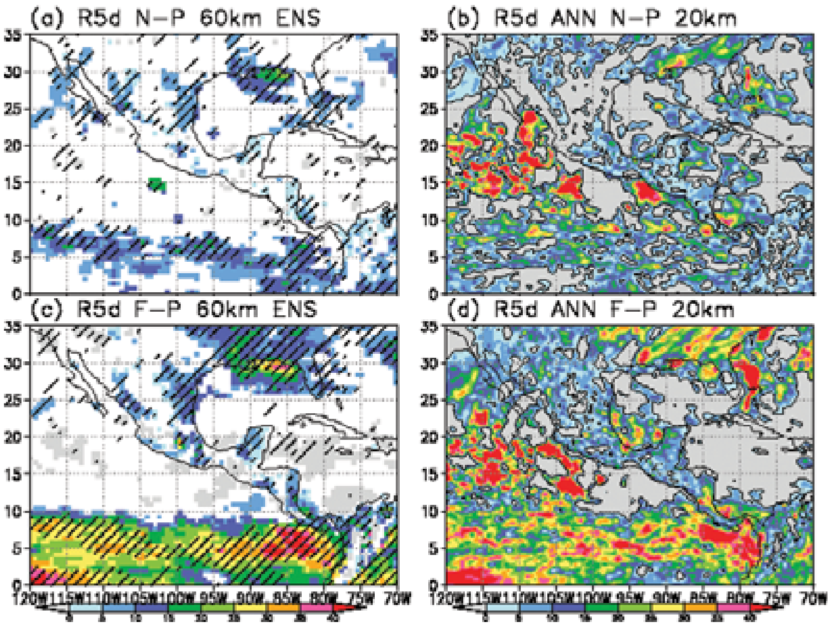
Source: Figure generated under the Memorandum of Understanding (MOU) between MRI and the World Bank.

and improvements in welfare for local communities. Overexploitation of groundwater has increased steadily over the last decades, leading to the depletion of many aquifers. Surface water resources are also overexploited, resulting in reduced water ecosystem functioning, including wetlands. The projections made through the Earth Simulator indicate that the annual average precipitation levels over most of Mexico and in particular in the Gulf of Mexico will present a negative anomaly by the end of the century. Figure H4 indicates the projected anomaly in annual winter precipitation toward 2100.

Global warming will result not only in changes in mean conditions but also in increases in the amplitude and frequency of extreme precipitation events. Changes in extremes are more important for the visualization of adaptation measures. Two extreme indexes for precipitation were calculated to illustrate changes in precipitation extremes over Mexico, one for heavy precipitation and one for dryness.

Figure H5 shows the changes in RX5D for the 60-km and 20-km resolutions. Throughout Mexico, RX5D is projected to increase in the future. The largest RX5D increases (rainfall intensification) are found over the Gulf of Mexico. At a higher resolution (20 km), the model projects even greater increases in RX5D by the end of the century.

Figure H5. Changes in the Five-day Precipitation Total



Source: Figure generated under the Memorandum of Understanding (MOU) between MRI and the World Bank.

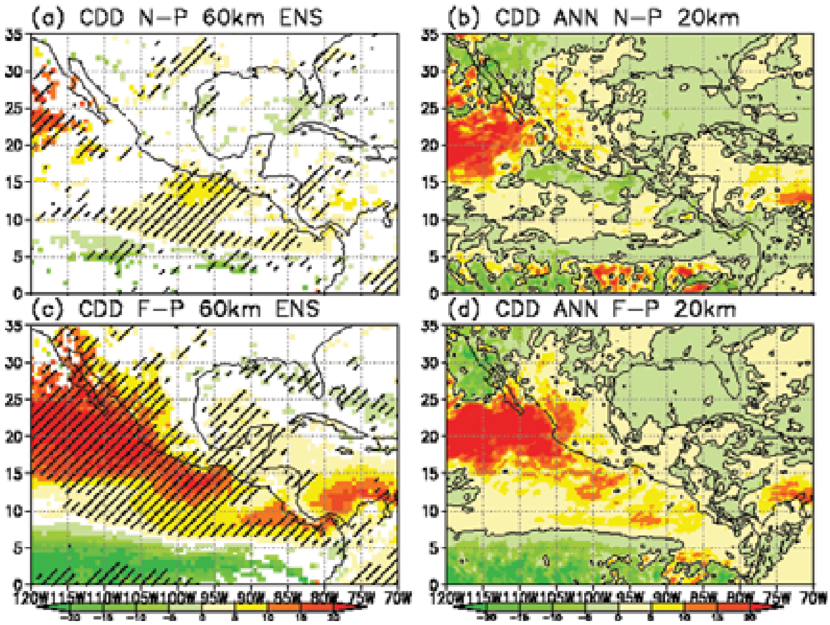
Figure H6 shows the projected changes in maximum number of CDD. A "dry day" is defined as a day with precipitation of less than 1 mm d^{-1}. Major CDD change is projected over the entire country. Droughts are projected to increase over time.

Hurricanes and storms are of particular concern for energy infrastructure located in the Gulf of Mexico. The Earth Simulator was again used to estimate how the pattern of storms may change as a consequence of climate by the end of century. The risk level of *cyclone storms* over Mexico varies from low to very high. As shown in Figure H7, areas with the highest risk are along the east coast, such as Tamaulipas state, the northern part of Veracruz, and northeastern area of the Yucatan Peninsula.

Historical hurricane data for the Gulf of Mexico over 1960–1995 also shows that the path of the most destructive hurricanes was over parts of the Yucatan Peninsula, in the north of the Veracruz region, and in the north of Tamaulipas state. It is clear evidence that these regions are vulnerable to natural hydro-meteorological events.

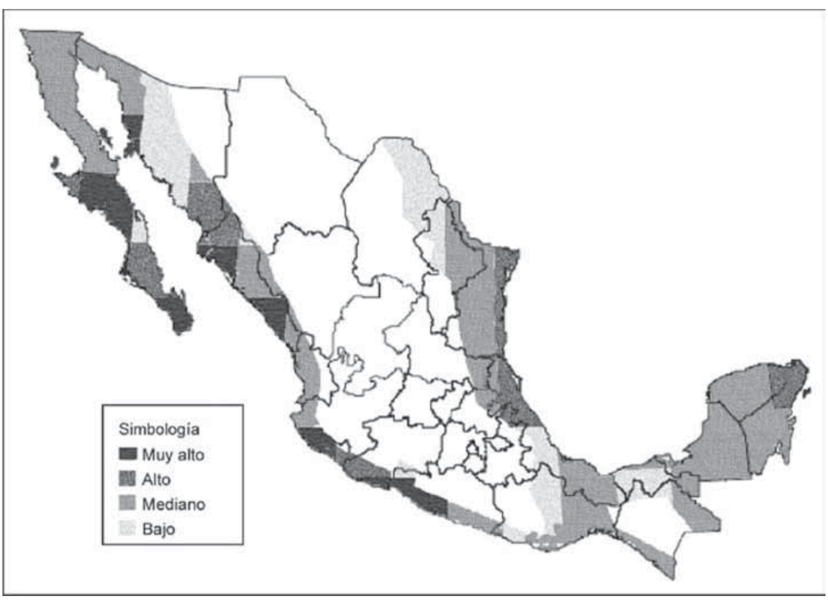
An ensemble of GCMs in the CMIP3 has been used to estimate potential changes in the genesis of tropical storms in the Caribbean. The estimate has been made on the basis of projected increases in sea surface temperature and consideration of other factors that affect the formation of hurricanes. The analysis was completed as part of the activities for formulation of the study, "Mexico: Adaptation to Climate Impacts in the Wetlands in the Gulf of Mexico" (CENAPRED, 2001).

Figure H6. Changes in the Number of Consecutive Dry Days (CDD)



Source: Figure generated under the Memorandum of Understanding (MOU) between MRI and the World Bank.

Figure H7. Areas of the Country at Risk of Cyclone Impacts



Source: CENAPRED, 2001.

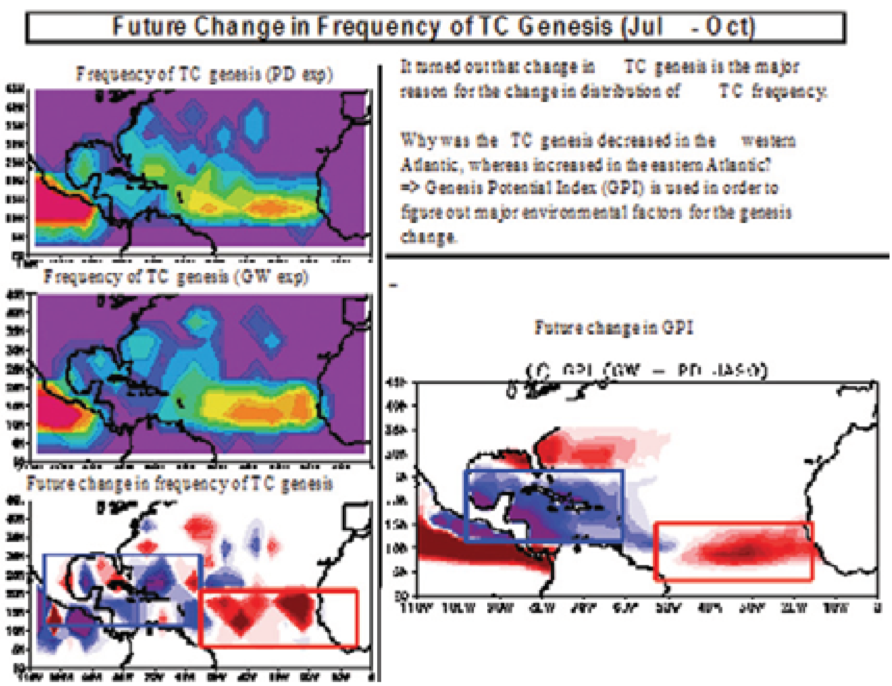
To estimate a change in tropical storm frequency and intensity, a GPI (Genesis Potential Index) was used, which reflects the change in conditions driving the formation of hurricanes. The GPI is a good metric to estimate climate-driven mean TC genesis derived from grid-scale environmental variables (Emanuel and Nolan, 2004). The index is described next.

$$GPI' = \left|10^{5}\eta\right|^{\frac{3}{2}}\left(\frac{RH}{50}\right)^{3}\left(\frac{V_{pt}}{70}\right)^{3}\left(1+0.1V_{s}\right)^{-2}\left(\frac{-\omega+0.1}{0.1}\right)$$

The first term in the equation refers to vorticity in the lower atmosphere, the second considers the impact of relative humidity, and last is the contribution of maximum potential intensity, vertical wind shear, and vertical motion. The results of the analysis applied to the Caribbean Sea and the Gulf of Mexico are presented in Figure H8. The analysis concludes that the genesis potential index for the eastern Atlantic will increase as a result of climate change, while it will decrease in the Caribbean, except for the area around the Gulf of Mexico.

Sea Level Rise. The IPCC Fourth Assessment Report indicates that low-lying coasts in Mexico are vulnerable to climate variability. The rate of sea level rise has been up to 2–3 mm/year. The rate of coastal erosion is also affected by heavy storms (IPCC, 2007b). Projected sea level rise indicates that the most vulnerable coastal low land in Mexico may be the Yucatan Peninsula. Figure H9 shows the impact of different levels of sea level rise in the Gulf Coast.

Figure H8. Change in Tropical Storm Frequency



Source: IPCC, 2007b.

Figure H9. Projected Sea Level Rise for Gulf of Mexico

Source: University of Arizona, 2008.

Impacts on Oil and Gas Infrastructure Located on Mexico's Gulf Coast

There is clear concern that climate change in the Gulf Coast may affect the development and operation of energy assets, including the oil and gas industry. Key concerns include anticipated variations in precipitation cycles, temperatures, and extreme events; an increase in the level of coastal storms; and sea level rise. PEMEX has made an assessment of some of these impacts on its installations (PEMEX, 2008, 2010). This assessment is summarized in Figure H10.

Oil and Gas Fields. Sixty-five percent (112 of 173) of Mexico's existing oil fields are located in the lowlands of Tabasco in areas that are very highly vulnerable to flooding, 33 percent are in vulnerable areas, and only 2 percent (4 oil fields) are located in moderately vulnerable areas. Infrastructure in the Tabasco region (for example, Tupilco and el Golpe) is also vulnerable to sea level rise and coastal erosion. The operation, accessibility, and maintenance of oil and gas field facilities could be affected by these vulnerabilities.

Figure H10. PEMEX's Infrastructure

Source: Rigzone, 2008.

Oil and Gas Pipelines. Eighty percent of pipelines (1,508 km) in the area of Llanura in the Tabasco region are located on lands with very high vulnerability to flooding. The remaining 20 percent (378 km) are found in areas with moderate vulnerability. In Veracruz state, 63 percent (2,102 km) of pipelines are located in areas sensitive to flooding, 28 percent (934 km) in areas of medium sensitivity, and the remaining 5.4 percent (181 km) in areas of very high sensitivity. Flooding of all pipelines could lead to widespread disruption of oil operations. Pipelines in several areas of the Gulf Coast are also susceptible to landslides and mudslides that may be critically exacerbated by severe rainfalls as projected to occur under high-resolution scenarios under the A1B emission trajectory.

Oil Refineries. PEMEX has six oil refineries. Their names, locations, and assessed exposure to climate risks are as follows:

1. Ing. Antonio Dovalí refinery and shipping terminal, located close to the Gulf of Tehuantecep in Salina Cruz in Oaxaca state (290 K barrels/per day of crude oil). In the past the area has been affected by extreme droughts that have resulted in petroleum activities being suspended due to a lack of water. The projected lengthening of dry periods may prolong work stoppages at the refinery unless alternative water supplies are ensured. In the past, torrential rains have caused partial flooding, and this could be exacerbated with the projected intensification of rainfall events. The refinery is additionally located in an area prone to hurricanes and associated storm surges. These installations are judged by PEMEX to be highly vulnerable to the consequences of climate change and merit an assessment of adaptation and other risk-reduction measures.
2. Miguel Hidalgo refinery is located in Tula, a semi-arid area of Hidalgo state (273,000 barrels/per day crude oil processed). It has limited exposure to the risks of extreme precipitation and flooding. The only potential risk is associated with heat waves that could affect workers at the refinery, although previous evidence of such phenomena does not exist.
3. Ing. Héctor R. Lara Sosa refinery in Cadereyta in Nuevo León state (207,000 barrels/per day crude oil processed) is assessed to be highly vulnerable to flooding due to its location in a low-lying area that is susceptible to overflows resulting from intense rain. The projected lengthening of dry periods may affect normal operations. An adaptation plan that includes an assessment of increased risks induced by climate change would be beneficial.
4. Ing. Antonio M. Amor refinery is located in Salamanka in Guanajuato state (196,000 barrels/per day crude oil processed). This area faces increasing water shortages. The lengthening of drought periods and increased competition for available water resources may require the adoption of alternative water supply and management procedures.
5. Gral. Lázaro Cárdenas refinery is located in Minatitlan in Veracruz state (169,000 barrels/per day crude oil processed) on the discharge plain of the Coatzacoalcos River. The refinery is exposed to potential intensification of tropical storms and subsequent storm surges. Installations are also vulnerable to projected sea level rise that may potentially require protection infrastructure or relocation of facilities.

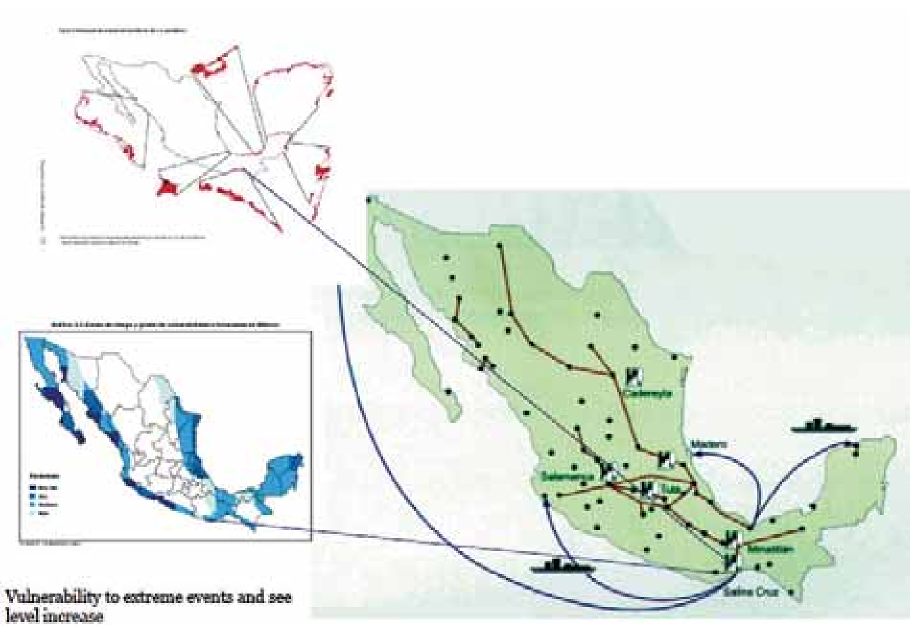
6. Francisko I. Madero refinery in Ciudad Madero, Tamaulipas (149,000 barrels/day crude oil processed) is located in the mouth of Panuco River and close to the Gulf Coast. The area is vulnerable to flooding and extreme events such as tropical storms and has been a traditional landfall for tropical storms. This may require measures to reduce risk to storm surges and flooding as well as possible structural damage.

Gas-Processing Facilities. PEMEX has 10 gas-processing facilities close to the Gulf Coast. Eight are located in the southeastern region of the country in the states of Chiapas (Cactus), Tabasco (Nuevo PEMEX, Ciudad PEMEX, La Venta), and Veracruz (Coatzacoalcos, Matapionche, Poza Rica, Arenque). Two remaining gas-processing installations are located in northeastern region of the country in Tamaulipas state (Burgos and Reynosa). Given their location, these facilities may also be exposed to the impacts of storm surges, flooding, sea level rise, and structural damage.

A comparison of areas susceptible to 1 m sea level rise and also those susceptible to extreme weather events with the location of refinery infrastructure is presented in Figure H11. It highlights the relative vulnerability of existing fuel infrastructure in Mexico.

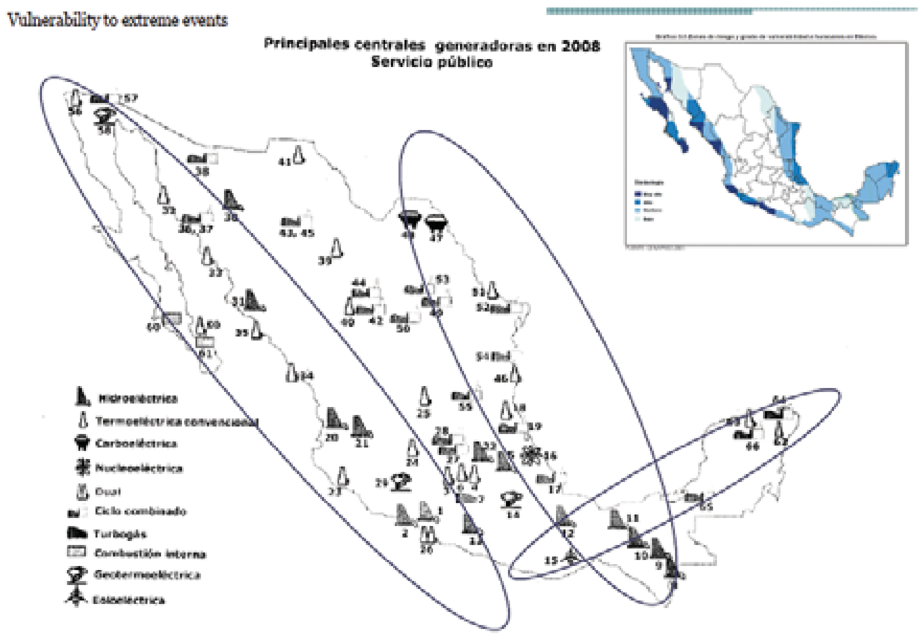
Figure H12, shows the areas historical susceptible to extreme weather events and the relative location of power plants. As an example, hurricane Emily in 2005 caused an estimated US$0.5 billion in losses as a result of loss of production and stoppages.

Figure H11. Mexico's Vulnerability to Extreme Events and Sea Level Rise



Source: Sheinbaum, 2010.

Figure H12. Mexico's Vulnerability to Extreme Events



Source: Sheinbaum, 2010.

Table H1. Potential Climate Impacts on Oil and Gas Infrastructure, Mexico's Gulf Coast

Asset	Climate change	Vulnerability	Climate impact
Oil fields	Flooding	65% very highly vulnerable (lowlands, Tabasco region) 33% vulnerable 2% moderately vulnerable	Impacts on operations and maintenance, accessibility
	Sea level rise, coastal erosion	65% very highly vulnerable (Tupilco and El Golpe, Tabasco region)	
Oil and gas pipelines	Flooding	80% very highly vulnerable (Llanura, Tabasco region) 20% moderately vulnerable (Tabasco region)	Disruption of operations
		5.4% very highly sensitive (Veracruz state) 28% medium sensitive (Veracruz state) 63% sensitive (Veracruz state)	Possible susceptibility to landslides, mudslides

(continued)

Asset	Climate change	Vulnerability	Climate impact
Oil refineries			
Ing. Antonio Dovali refinery and shipping terminal	Heavy rain and flooding	Highly vulnerable	Lack of water could suspend operations and cause prolonged work stoppage
	Hurricanes and storm surges		
	Drought		
Miguel Hidalgo refinery	Extreme precipitation/ flooding	Limited exposure	
	Heat waves	No previous impacts	Impacts on workers possible
Ing. Hector R Lara Sosa refinery	Flooding	Highly vulnerable	Overflows
	Lengthening of dry periods		Impacts on normal operations
Ing. Antonio M Amor refinery	Increased water shortages		
	Longer droughts		
	Increased competition for water		
Gral Lazaro Cardenas refinery	Intensification of tropical storms and storm surge	Exposed	
	Sea level rise	Vulnerable	Possible protection of infrastructure/ relocation needed
Francisko I Madero refinery	Flooding, extreme events (tropical storms)	Vulnerable	Possible need to reduce risk to storm surge, flooding, and structural damage
Gas-processing facilities	Storm surge	Exposed (Burgos and Reynosa, Tamaulipas state)	Possible structural damage
	Flooding		
	Sea level rise		

Source: Generated by authors.

Notes

1. Hydropower, fuel-wood, bagasse, geothermal, and wind energy.
2. Mexico ranks 13th in the world in total GHG emissions and is the second largest emitter in Latin America after Brazil. It accounts for 1.4 percent of global CO_2 emissions from fossil fuels, excluding other GHGs and land-use change and forestry (LUCF).
3. The difference between total GHG emissions and CO_2 emissions from the consumption and flaring of fossil fuels is due to other GHGs and emissions from land-use change.
4. The projections were prepared under a cooperation agreement between the Meteorological Research Institute of the Japan Meteorological Agency (MRI/JMA), Instituto Nacional de Ecología (INE), and the World Bank. The projections were generated using an atmospheric GCM of MRI/JMA; a global hydrostatic atmospheric general circulation model with a horizontal grid size of about 20 km (Mizuta et al. 2006) that offers unequaled high-resolution capability. This model is an operational short-term numerical weather prediction model of JMA and is part of the next-generation climate models for long-term climate simulation at MRI. The outputs of the MRI/JMA GCM represent the anticipated changes in climate conditions induced by global emissions of greenhouse gases (GHG). Although the global 20-km model is unique in terms of its horizontal resolution

for global climate change studies with an integration period up to 25 years, available computing power is still insufficient to enable ensemble simulation experiments. This limits its application to a single-member experiment. To address this limitation, parallel experiments with lower-resolution versions of the same model (60-km, 120-km, and 180-km mesh) were performed. In particular, ensemble simulations with the 60-km resolution have been performed and compared with the 20-km version for this study, thereby increasing the robustness of the projections.

5. When initially developed, the A1B scenario was thought to be a description of the middle range of GHG emission scenarios. Today's emissions trajectory is already well above the A1B scenario. Therefore, this scenario may no longer represent a plausible future.

6. For instance, climate change and its manifestations at a regional level will depend on elevation. Through the use of regional scenarios, it is possible to observe how such changes will vary in distances of a few dozen kilometers. Even more, the role of complex topography and how it affects the projected changes in extreme events may be identified with a high-resolution model such as the one available in the Earth Simulator.

Appendix I. Case Study: Regulation for the Aviation Industry

The aviation industry offers useful experience and insights that could be applied when establishing tailored weather and climate services for the energy sector. Weather and climate information is a vital for the air transport industry. It requires the continuous sharing of weather information, operationally and globally, to preserve the safety, efficiency, and sustainability of the industry. Worldwide information networks have been established (from weather watch services to climate monitoring and prediction systems) to support this need. These networks successfully:

a. Maintain information services and sustainable systems without exception, even in developing countries;
b. Apply the same efficiency standard worldwide;
c. Integrate regional and global information systems; share operational, planning, and research costs; and have government support; and
d. Are well-organized, secure, economical, and highly regulated.

The aviation sector meets these objectives by:

1. Identifying, standardizing, and agreeing to information needs on a global basis through the International Civil Aviation Organization (ICAO). Users are trained in the interpretation of weather and climate products and services.
2. Collecting weather/climate information at airport sites. A weather station located at the airport is the best and most reliable source of climate information. It is an important reference for monitoring climate change because of its secure location, professional operation, and user control (for example, pilot security reports are made at each aircraft take-off and landing).
3. Professionally delivering weather/climate services on-site. Staff are qualified under WMO standards
4. Integrating services with other aviation security services and delivering them directly and on-site to the final user or the coordinating agency (for example, air transport navigation and security).
5. Communicating information nationally and globally with support from a Regional Climate Watch Network (for example, Bangui for the Central African Republic with 14 stations). Data are communicated worldwide within five minutes of collection. Specialized communication structures are accessible to local, national, regional, and global users to facilitate appropriate and timely decisions.
6. Providing global, unrestricted access to weather information. Climate information is available for commercial planning to optimize routing time and fuel consumption.
7. Supporting the cost of providing air security and economic services (highly dependent on weather and climate) through the air transport industry. Regular negotiations are held under the auspices of the International Air Transport Association (IATA, composed of all of the airline companies), with the support of the ICAO and WMO.
8. Organizing research and capacity building at a regional and global level to realize economies of scale and standardize training according to WMO and ICAO standards and IATA needs.

Appendix J. Access to Predictions

Predictions to ~15 Days—Access by NMHSs to predictions from the major centers is straightforward, although the precise situation varies by recipient country. In principle all WMO Member State NMHSs should have rapid access to short-range forecasts via the WMO GTS (Global Telecommunication System). Additional satellite-based systems, such as Meteosat Data Distribution in Africa, assist within the GTS structure to distribute predictions to countries with slow or nonexistent Internet connections. The authors are not aware of any WMO Member States in which there is no access to prediction information. Unfortunately, international centers tend to produce forecasts tuned to higher latitudes, with less research focus placed on skill in lower latitudes.

The ability of forecasters within each country to provide information tailored to the needs of the energy sector varies markedly. In general, developing countries focus their attention on delivery of deterministic predictions at the sacrifice of ensemble predictions, whereas the use of the ensembles would be beneficial to the energy sector; this topic is discussed further in Chapter 5, "Uncertainty in Predictions."

Delivery and interpretation of forecast information is a major issue in those countries in which no customized service to the energy sector yet exists or the service is rudimentary. The most common delivery approaches are via printed and electronic media, often in formats designed for the general public and lacking the details required by the energy sector. Information delivery via developing-country NMHS websites has matured steadily over recent years, although the additional details required by the energy sector may not be included on these sites. Customized prediction services have yet to be introduced in many developing countries.[1] The same follows for electronic links to decision makers within the energy sector and direct prediction information for subsumption into energy sector models.

Monthly to Inter-Annual Outlooks—Various sources of predictions are available on monthly to inter-annual time scales. A number of leading forecasting centers, as well as research organizations and universities, run operational ensemble predictions using a variety of numerical models,[2] the most complex being fully coupled atmosphere–ocean models, often similar to those used both for weather forecasts and for climate change projections.[3] In general, access to predictions from WMO-linked centers is available either gratis or through agreement, while access to research centers and universities is often made available freely through the web.

In addition to the numerical products, numerous empirical products are available, either in parallel with the numerical products or separately. NMHSs and universities in many developing countries have created empirical models specific for a country or a region. Whereas, in principle, numerical models can predict any hydro-meteorological/climate parameter, empirical models in general focus on basics such as temperature and rainfall for which adequate observational time series are available with which to calibrate the models. Empirical models might be used to predict any weather parameter for which time series are available and, additionally, need not be restricted to weather parameters alone. For example, because river flows and malaria are directly linked to rainfall, which in turn is linked to sea surface temperatures, empirical models already exist that provide direct predictions of river flows (Met Office, 2008) and malaria (RBM, 2001; IRI, 2010) incidence without using any intermediate rainfall prediction step. There is no reason why such empirical links might not be investigated in the energy sector.[4]

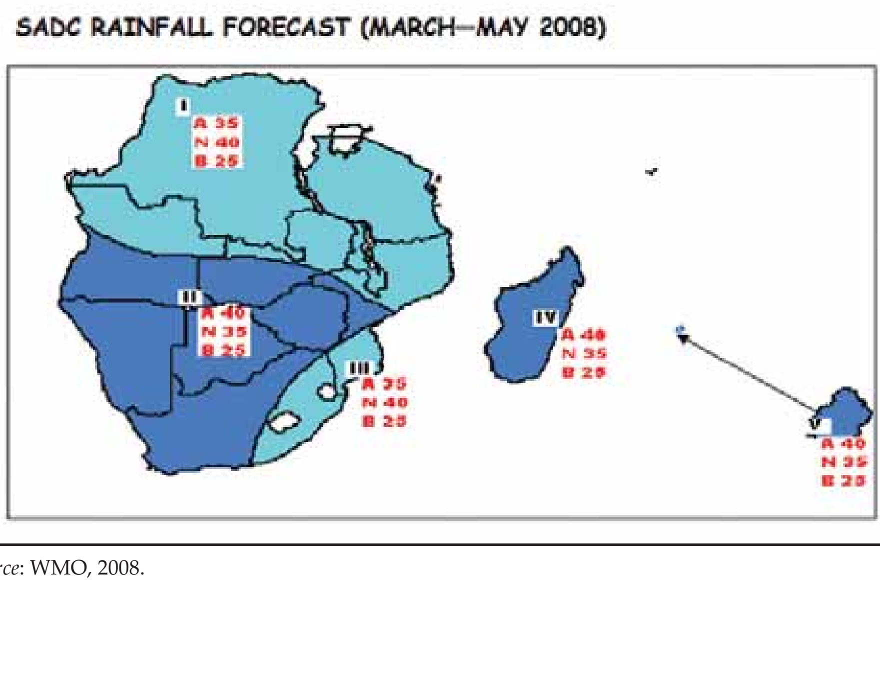
Predictions on longer time scales cannot provide the same spatial and temporal detail as shorter-time-scale predictions, and normally are provided as averages over a season (although shorter periods, such as a month, are sometimes used) and as averages over areas of size, say, 2° latitude by longitude, whether produced by numerical or statistical techniques. Expertise in producing and interpreting longer-range predictions has grown substantially in recent years in developing countries. Nevertheless, priorities in many countries continue to emphasize shorter-range services over climate services, despite the readily made argument that, certainly in tropical countries, climate variability is more critical to society than weather variability.

Interpretation of outlooks into sectoral decisions remains an area that requires further development from both the forecaster and the user; it is probably reasonable to state that many forecasters in addition to users do not understand fully the issues related to these forecasts, as discussed in Chapter 5 under "Uncertainty in Predictions." Additionally, formats used to supply predictions are often rudimentary, frequently being designed to simplify the information at the expense of removing critical details required by the user. A recent southern African seasonal forecast is illustrated in Figure J1.

One type of weather system that is best predicted through outlooks and that impacts the energy sector is drought; likelihoods of droughts developing, continuing, or terminating may be estimated through these predictions. Outlooks can also be used to predict extended periods of above- or below-normal temperatures on average, or prolonged periods of above-average rainfall.

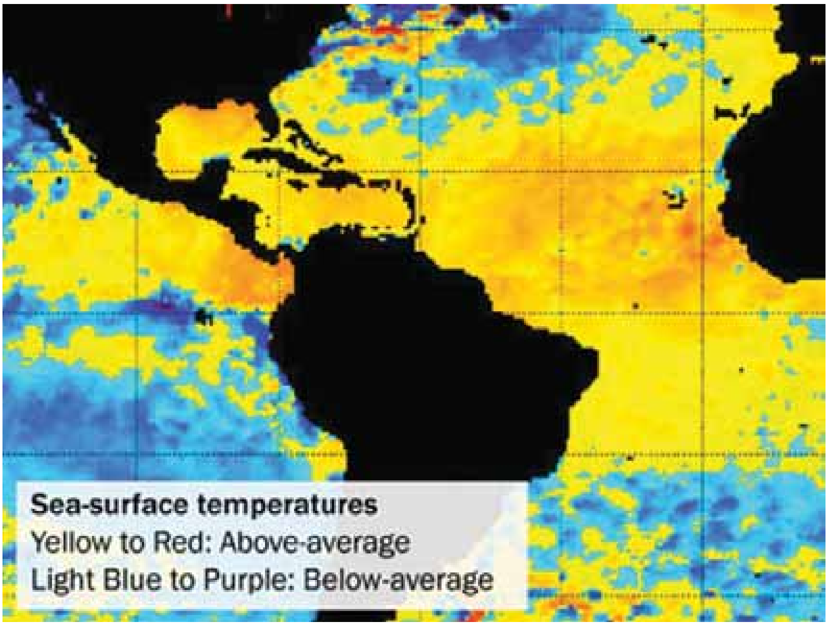
Another example is provided by the recently released forecast by the International Research Institute for Climate and Society for the upcoming Atlantic hurricane season: "*The Atlantic hurricane season has officially started, and the International Research Institute*

Figure J1. South African Development Community (SADC) Rainfall Forecast (March−May 2008)



Source: WMO, 2008.

Figure J2. Sea Surface Temperatures in the North Atlantic



Source: The International Research Institute for Climate and Society, courtesy of NOAA.

for Climate and Society has issued its updated seasonal hurricane forecast for the region. The results continue to indicate that an above-normal season is very likely. This could spell trouble for highly vulnerable Caribbean nations such as Haiti, still reeling from the effects of a 7.0 magnitude earthquake on January 12, 2010. On top of this, other forecasts point to increased thunderstorm activity for the region as well" (Holthaus, 2010). This is illustrated in Figure J2 from NOAA: above-normal temperatures in the North Atlantic are strongly influencing recent forecasts that call for a robust 2010 hurricane season.

Notes

1. A broad discussion on the use and delivery of seasonal forecasts is provided by Harrison and Williams, 2008.
2. *Numerical model* and *dynamical model* are used interchangeably. Likewise for *empirical* and *statistical models.*
3. See, for example, ECMWF, 2010
4. An example for dam control is given in Chapter 5.5 and a second example is in Brayshaw et al. (2010) that considers empirical links between UK winter wind power generation and the North Atlantic Oscillation (NAO), an atmospheric metric that, in effect, measures the strength of the winds across the Atlantic and western Europe.

Appendix K. Frameworks, Methodologies and Tools for Climate Risk Management and Decision Making Under Uncertainty

Examples of frameworks, methodologies and tools to guide Climate Risk Management and decision making under uncertainty are provided below:

Climate Change Risk Screening Tools OECD (2009) and Olhoff and Schaer (2010) provide useful overviews and summaries of available climate risk screening tools. Some examples are provided below.

Asian Development Bank (ADB): Climate Proofing—A Risk-Based Approach to Adaptation (ADB, 2005). This presents six case studies (two infrastructure development projects, two community development planning and regulation activities, and two national strategic development plans) from the Pacific region applying the Climate Change Adaptation through Integrated Risk Assessment approach (IGCI, 2010). The approach builds on five main components:

1. capacity building, including awareness raising and institutional strengthening;
2. data, tools, and knowledge related to climatic change variability and extremes and their effects;
3. risk assessments that translate scientific data and knowledge into information relevant to decision making on adaptation;
4. mainstreaming of climate change and adaptation information into policies, plans, and development strategies; and
5. monitoring and evaluation for reassessing risk and response capabilities over time.

Economics of Climate Adaptation: Shaping Climate Resilient Development—A Framework for Decision Making (ECA, 2009). Focusing on the economic aspects of adaptation, this study outlines a fact-based risk management approach that national and local leaders can use to understand the impact of climate on their economies—and identify actions to minimize that impact at the lowest cost to society. A quantitative decision-making framework and methodology is developed, built around two sets of tools:

1. tools to quantify a location's "total climate risk"; and
2. cost-benefit techniques applied to evaluate a selection of feasible and applicable measures to adapt to the expected situation

The methodology is tested in eight case studies, one of which addresses health and power risks arising from drought in Tanzania.

ESMAP/World Bank: Hands-on Energy Adaptation Toolkit (HEAT) (2010). HEAT,[1] a Hands-on Energy Adaptation Toolkit, developed by the Energy Sector Management Assistance Program and the World Bank, documents the lessons, experience, and process followed in implementing a pilot Climate Vulnerability Assessment program in Albania and Uzbekistan (2009–2010). HEAT is designed to lead users through a stakeholder-based semi-quantified risk assessment of climate vulnerabilities and adaptation options in the energy sector at a national level.

OECD: Guidance on Integrating Climate Change Adaptation into Development Co-Operation (OECD, 2009). The OECD approach incorporates adaptation into partner country processes and institutions, but the guidance is equally useful for policy makers and practitioners in developing countries. The guidance note applies an integrated approach to link climate adaptation needs and priorities to policy processes at the national, sector, local, and project levels. The main objectives of the guidance note are:

1. to promote understanding of the implications of climate change on development practice and on the need to mainstream climate adaptation;
2. to identify appropriate approaches for integrating climate adaptation into development plans and activities at national, sector, local, and project levels; and
3. to identify practical ways for donors to support developing country partners in efforts to reduce their vulnerability to climate change.

The OECD guidance identifies pragmatic methods, resources, and tools at each level of analysis, but it does not provide detailed operational guidance for implementing action on the ground.

Notes

1. www.esmap.org/esmap/heat.

Appendix L. National and Regional Adaptation Initiatives

Government-Led Adaptation Initiatives in the Energy Sector

- **Australia's** National Framework for Adaptation (2007) includes the energy sector as part of settlement's, infrastructure and planning but not as an independent sector (Australian government, 2007). The government's White Paper "Securing Australia's Energy Future" (2004) briefly mentions that investments in adaptation are required; however, the main focus is on greenhouse gas mitigation.
- **United States:** In 2008, the U.S. Climate Change Science Program report "Effects of Climate Change on Energy Production and Use in the United States" (Wilbanks et al., 2008) provided, for the first time, science-based knowledge for adaptive management and planning to support national policy formulation for the energy sector.
- **Canada's** Council of Energy Ministers affirmed the importance of developing adaptation strategies for the energy sector in 2007. A working group consisting of federal, provincial, and territorial institutions was established to address the impacts of climate change on Canada's energy infrastructure, energy consumption, and electrical power supply (Canadan government, 2009).
- **The European Union's** Climate Change Programme in 2005 (Colls et al., 2005) first addressed the integration of adaptation measures in climate-sensitive sectors. At a national level, adaptation strategies are under way in a number of countries such as Denmark, the United Kingdom, and Finland, and awareness of the need to enhance coordination for adaptation both within and between countries is developing.
- **National Adaptation Plans of Actions (NAPAs) in developing countries:** In spite of the vulnerability of energy supply in the least developed countries, policy and planning frameworks for vulnerability and adaptation do not include energy. In a recent analysis on the role of the energy sector in 41 African countries' NAPAs, it was found that only 3.7 percent of 455 adaptation projects proposed were related to the energy sector (Mamouda, 2009).

Regional and National Examples

ESMAP pilot vulnerability assessments—An example from Albania provides detailed and rich insights into the important role of weather and climate information for management of energy sector vulnerability (Hancock and Ebinger 2009; World Bank, 2010d). With over 90 percent of domestic electricity production coming from hydropower, Albania is highly vulnerable to climate variability and change. Access to weather forecasts and climate databases is therefore paramount for sound energy planning and operating practices to ensure energy security. The national hydro-meteorological institutions providing data and making forecasts could benefit from improved coordination. The study examines options to improve weather and climate information for: large- and small-scale hydro-power plants, power transmission and distribution, thermal power plants, and wind, solar, and energy demand (Hancock and Ebinger, 2009).

Sub-Saharan Africa's power supply is inadequate and unreliable, with frequent blackouts, high prices, and low rates of access to the grid; 89 percent of the population relies on natural resources for energy supply (for example, wood, animal dung or crop waste, hydro and solar power), and the energy sector is therefore highly exposed to climate variability (HELIO International, 2007). In East Africa, hydropower comprises about 80 percent of electricity generation (Karekezi et al., 2009), and a key priority for Uganda, Kenya, Tanzania, and Ethiopia is to reduce climate vulnerability. Another adaptation priority for Africa is to focus on bottom-up approaches for energy adaptation rather than top-down approaches relying on climate model scenarios and forecasting approaches (HELIO International, 2007). Bottom-up approaches focus on local resilience and energy planning. Most people, particularly in rural areas, rely on local energy resources that are vulnerable to climate variability and change. It is therefore important to recognize the value of indigenous knowledge, local coping strategies and social capital (for example, insurance programs against climate risks).

The Caribbean is highly exposed to extreme weather events—such as the El Niño-Southern Oscillation (ENSO) that has consequences for weather around the globe—including tropical storms, floods, hurricanes, and droughts (Contreras-Lisperguer and Cuba, 2008). Energy production and use are affected; both traditional energy (water availability for cooling and hydropower generation, damages to energy infrastructure) and renewable energy (the vulnerability of hydro power systems, energy crops, wind energy, solar power, geothermal energy and wave, tidal, or ocean thermal energy). Sensitivity studies showing the effects of climate change should be included in the energy planning processes to allow uncertainties to be assessed and recognized.

Sweden's energy sector—In 2005 Elforsk examined the effect of climate change on Swedish plant operations, production conditions, and energy use. The study looked at how to project undesirable consequences and what long-term measures could be necessary to manage them (Gode et al., 2007). The study did not reveal an acute need for adaptation and instead indicated increased production potential for both hydro and wind power. For wind power, the growth potential is 5–20 percent based on an installed capacity of 4,000 MW. Bioenergy potential could also increase in view of the 5–10 percent growth projected for forestry and agricultural production. A warmer climate will reduce heating needs by approximately 15 TWh.

The European electricity sector—A study of climate impacts and the cost of adaptation (Reiter and Turton, 2009) evaluated the impact of higher temperatures on the energy conversion to 2050. The average global temperature is estimated to increase by 2°C during this period. The rise in Europe's electricity demand due to climate change is estimated to be around 5 percent by 2050. In southern European countries demand could rise 7–10 percent per year by 2050. The study emphasizes that rising demand for electricity for space cooling in summer coincides with lower efficiency and availability of power generation. Associated additional investment costs for Europe increase by about 2 percent, with more than 50 percent of this being needed in southern Europe.

Renewable energy in Nordic countries—[1] Two large renewable energy research programs have addressed the energy system in Nordic countries: "Impacts of Climate Change on Renewable Energy Sources: Their Role in the Nordic Energy System"

(Fenger, 2007) and "Climate and Energy Systems" (Office, 2010). The studies assessed the changes in renewable energy production in the next 20–30 years due to global warming (Office, 2010). In the next 50–100 years, the studies found that the direct impact of changes in average climate change variables, such as a moderate increase in hydropower or a decrease in heating demand, are marginal compared to technical, economic, and political conditions, which are likely to be very different, but hard to predict, compared to today (Fenger, 2007).

Notes

1. Denmark, Sweden, Norway, and Finland.

Appendix M. Global Framework for Climate Services

At the World Climate Conference-3 (WCC-3, Geneva, 31 August–4 September 2009), participants from a broad range of socioeconomic communities, including the energy sector, acknowledged that their activities were sensitive to climate. They recognized that decisions for planning, operations, risk management, and adaptation to climate change and variability (covering time scales from seasonal to centennial) could be improved with better climate knowledge and access to and use of actionable information and products tailored to their needs.

WCC-3 participants called for climate user interface mechanisms to link and integrate climate information, at all levels, between providers and users. They supported the establishment of a **Global Framework for Climate Services** (GFCS) for: *"The development and provision of relevant science based climate information and prediction for climate risk management and adaptation to climate variability and change, throughout the world."*

The needs of the user community are diverse and complex. Understanding the specific information requirements of different users in their decision-making processes requires closer interaction between climate scientists and experts from other sectors and disciplines. The GFCS aims to increase and improve interactions between climate service providers and those who make use of the services.

The GFCS will support partnerships between climate scientists; sector-specific and multi-disciplinary scientists; academia; sector-focused agencies such as the International Atomic Energy Agency (IAEA), International Energy Agency (IEA), United Nations Industrial Development Organization (UNIDO), World Health Organization (WHO), United Nations Environment Programme (UNEP), and the World Tourism Organization (UNWTO); the IPCC; co-sponsored programs World Climate Research Programme (WCRP) and Global Climate Observing System (GCOS); WMO's Public Weather Services Program; and nongovernmental organizations (for example, IFRC). This will facilitate collation of interdisciplinary data, information, and knowledge to develop user-targeted products.

GFCS will have four main functions:

1. User Interaction Mechanism;
2. World Climate Services System;
3. Climate Research; and
4. Observation and Monitoring.

While the latter two are already well established, the first two are new efforts and are discussed further below.

GFCS's **User Interaction Mechanism** will facilitate dialogue across disciplines and users to understand information requirements and develop effective climate services. User interaction will be required at various levels: at a global level to address applied research requirements and feedback; at a regional level to address the specific requirements of products according to regional economic, climatic, and physical characteristics; and at a national level to address sector- and user-specific needs according to national and local conditions.

Given that climate processes are global in character, the flow of information from global to local scales is essential and has to be ensured. For the effective delivery of climate information, it will be essential to put in place appropriate institutional mechanisms to gather, generate, exchange, and disseminate quality information at all levels.

The World Climate Services System (WCSS) will coordinate the development and provision of climate information for various socioeconomic sectors. The global and regional centers of excellence proposed under the GFCS will make regional and local climate information available to national climate services. The network will facilitate the flow of information by setting standards and protocols, and by sharing information, experience, and knowledge.

National Climate Services (NCSs) provide science-based climate information to government institutions and socioeconomic sectors. The services are created through a collaborative network of entities, known as the NCS community. The WCC-3, in deciding to establish a GFCS to strengthen the production, availability, delivery, and application of science-based climate monitoring and prediction services, envisioned NCSs. An illustrative example of a newly established NCS is that run by NOAA-USA and launched in 2010. It has an open source climate information portal, www.climate.gov that builds on experience from the Information System on Drought Risk Management under the National Integrated Drought Information System.

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