COUNTRY ENERGY SECTOR VULNERABILITY ASSESSMENTS PROGRAM

Helping Countries Prepare an Effective Energy Sector Response

Climate Impacts on Energy Systems

Key Issues for Energy Sector Adaptation

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THE WORLD BANK

ESMAP

Energy Sector Management Assistance Program

Preview
(not for citation)

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.

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% 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 2C 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% 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 investment and action.

The key messages for this report are:

1. **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, is 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 (e.g., water, agriculture).

2. **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]

3. **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.

4. **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.

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 (e.g., 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.

[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.

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.

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

“*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.

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 (ECA) is the only region with observed large inter-annual temperature variations; up to about 5ºC 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 (e.g., 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.

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 variables 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 (Annex 3 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).

Figure ES 1: (Top) Patterns of linear global temperature trends over the period 1979 to 2005

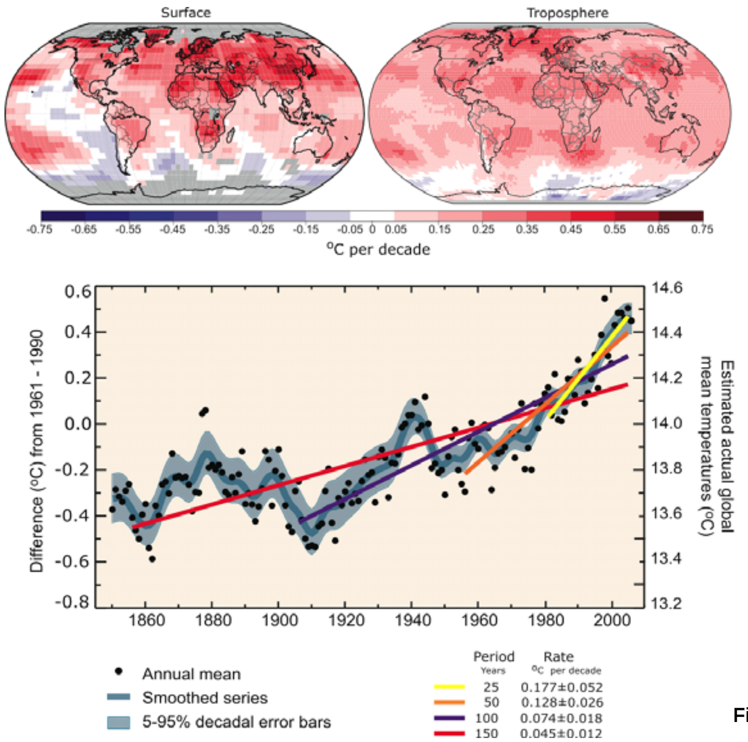


Figure TS.6

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% 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.
Source: IPCC, 2007a.

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% 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. 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 (e.g., 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 Wm^{-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 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 (e.g., inefficiencies in energy and water use mean energy services are vulnerable and have less capacity to deal with change).

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 (2.2a)	Large errors in observed seasonal mean (2.1c)	Large observed variability (2.1b); sizeable projected changes in variability (2.2a)	Large errors in observed seasonal mean (2.1c); sizeable projected changes in variability (2.2a)		Large errors in observed seasonal mean (2.1c)
10-meter wind				Large observed variability over ocean (2.1b)	Large observed variability over NW Africa (2.1b)	
Solar radiation	Large errors in observed annual mean (2.1c); sizeable projected changes in high-end extremes (2.2c)			Large errors in observed annual mean (2.1c)	Sizeable projected changes in high-end extremes (2.2c)	Large errors in observed annual mean (2.1c); sizeable projected changes in high-end extremes (2.2c)
Sea level	Large observed changes (2.1d)					Large observed changes (2.1d)
Permafrost			Risk of degradation and reduction (2.2e)			
Sea ice	Reported acceleration of melting of Greenland and Antarctic ice sheets (2.2d)					

Note – hotspots listed were identified in Chapters 2.1 and 2.2, and hence are not comprehensive across all variables/statistics combinations. "Observed" refers to either direct observations or to outputs from re-analyses.

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 (e.g., 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 (Metz et al., 2007), 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 (e.g., irrigation). Temperature tolerances of energy sector infrastructure

[3] Many studies investigate the relationship between energy and climate, but without focusing on global climate change.

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 appears inevitable, 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% 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 (e.g., 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

- 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

Item	Relevant Climate Impacts			Impacts on the Energy Sector
	General	Specific	Additional	
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		Positive or negative impacts
Wave and tidal energy	Ocean climate	Wind field characteristics No effect on tides	Strong non-linearity 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	Reduced	Extreme events	Reduced energy generated

Item	Relevant Climate Impacts			Impacts on the Energy Sector
	General	Specific	Additional	
	efficiency Cooling water availability	efficiency Increased water needs, e.g., during heat waves		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
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 non-energy crops for land and water resources	Increased vulnerability and uncertainty Increased costs

Adaptation Is Not an Optional Add-on

In the global climate change context, adaptation can be described as a combination of factors 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% 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 (Coonor et al., 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 (e.g. 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

[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.

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, non-governmental 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, e.g., a

[6] Thawing is likely to benefit some activities (e.g., 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).

warmer-than-normal winter) and insurance (for low-probability but catastrophic events, e.g., 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 (e.g., 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% 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 – DSM). 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 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)

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

ENERGY SYSTEM		TECHNOLOGICAL		BEHAVIORAL		
		"Hard" (structural)	"Soft"(tech. 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 re-circulating 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 (e.g. 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 Williamson et al., 2009.

While the fundamentals of risk management are already widely appreciated and practiced within the energy sector (e.g., 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 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.

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:[9]</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>

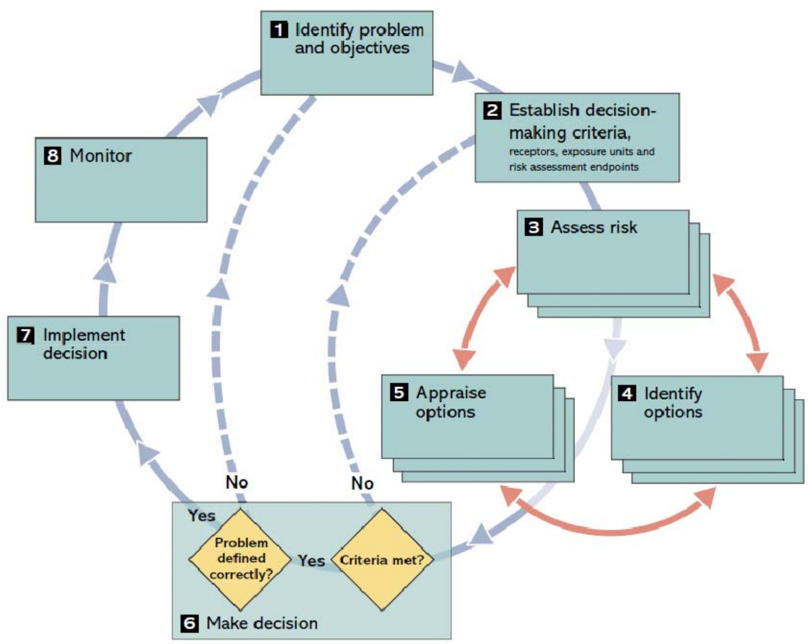
Proper integration of climate risks in decision-making processes will minimize the risk of over-, under-, and mal-adaptation. There is a close link with decision-making criteria (Figure ES.2): *What is the "right" level of adaptation? How climate resilient do we want our actions to be?* Willows and Connell (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, etc.) or on expected climate futures. They

[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 (e.g., malaria) and agriculture (e.g. crop growth).
[9] The World Bankand other organizations, refer to CRA and the planning of climate proofing together as "climate risk screening" or equivalent, http://beta.worldbank.org/climatechange/content/note-3-using-climate-risk-screening-tools-assess-climate-risks-development-projects.

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 important 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 non-energy crops.

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



Source: Willows and Connell, 2003.

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 (e.g., 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 mal-adaptation.

There is a need for research and practical tools to address all aspects of risk management under climate uncertainties. The International Finance Corporation 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.[10]

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

[10] http://www.ifc.org/ifcext/climatechange.nsf/Content/AssessingClimateRisks

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.

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

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, e.g., for demand, pollution, or emissions modeling	
Access to and delivery of hydro-meteorological/climate information appropriate to requirements	

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 (e.g., 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 (e.g., 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.

1. **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.

2. **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.

3. **Develop project screening tools:** Develop templates to screen individual energy projects for climate vulnerability and risks, either retrospectively or during project planning and implementation.

4. **Develop adaptation standards for the energy sector:** Such standards should cover engineering matters and information requirements.

5. **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.

6. **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.

7. **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.

8. **Identify policy Instruments** needed to support climate impact management.

9. **Support capacity building:** Increase the capacity of key stakeholders including energy sector policy makers, regulators, and operators, for climate risk management.

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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, Marcelino Madrigal, and Alejandro Deeb. The team was assisted by Irene Leino, Oeyvind Lier, and Vanessa Lopes.

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The financial and technical support by the Energy Sector Management Assistance Program (ESMAP) is gratefully acknowledged. ESMAP is a global knowledge and technical assistance trust fund program administered by the World Bank and assists low- and middle-income countries to increase know-how and institutional capacity to achieve environmentally sustainable energy solutions for poverty reduction and economic growth. ESMAP is governed and funded by a Consultative Group (CG) comprised of official bilateral donors and multilateral institutions, representing Australia, Austria, Denmark, Finland, Germany, Iceland, the Netherlands, Norway, Sweden, the United Kingdom, and the World Bank Group.

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