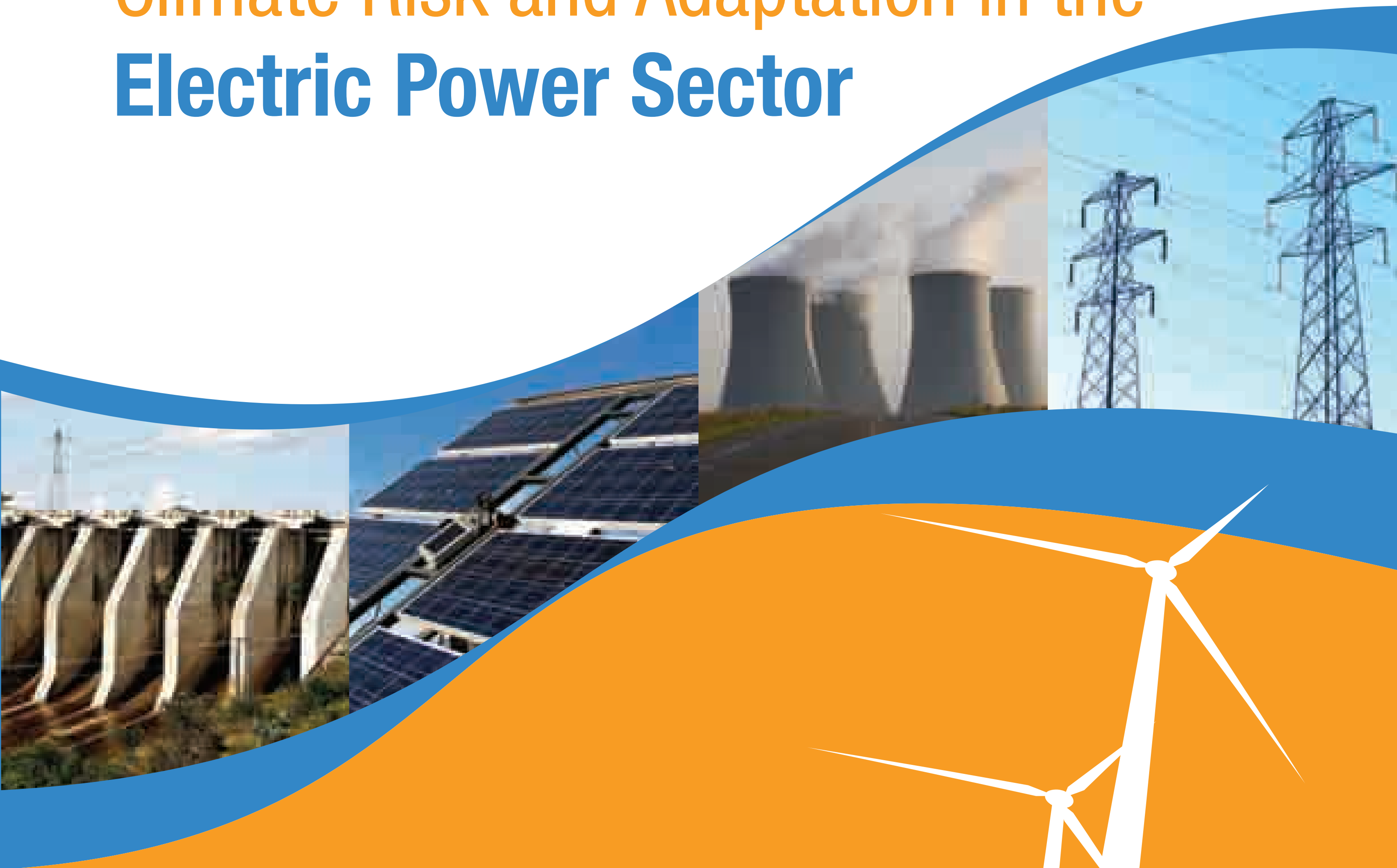
ADB

Climate Risk and Adaptation in the
Electric Power Sector



Asian Development Bank

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Climate Risk and Adaptation in the **Electric Power Sector**

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Asian Development Bank
6 ADB Avenue, Mandaluyong City
1550 Metro Manila, Philippines
Tel +63 2 632 4444
Fax +63 2 636 2444
www.adb.org

For orders, please contact:
Department of External Relations
Fax +63 2 636 2648
adbpub@adb.org

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Foreword

Between 2005 and 2030, primary energy demand in Asia and the Pacific is expected to grow at an annual rate of 2.4%, and demand for electricity at 3.4%. Developing member countries (DMCs) of the Asian Development Bank (ADB) will account for the bulk of these increases.

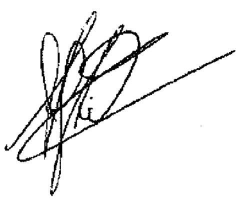
By 2030, fossil fuels (coal, gas, and oil) are expected to continue to generate more than 70% of electricity in the DMCs. The power sector alone will continue to contribute approximately half of the region's total carbon dioxide (CO_2) emissions by 2030, with a corresponding contribution to the increase in atmospheric concentration of greenhouse gases. In response to this challenge, ADB has adopted a number of initiatives (including the Energy Efficiency Initiative and the Asia Solar Energy Initiative) and programs (such as the Clean Energy Program) to support low-carbon investments in the energy sector. ADB's total clean energy investments reached $2.1 billion in 2011. Renewable energy and energy efficiency account for the bulk of these investments.

To date, far less attention has been devoted to the exposure and vulnerability of the power sector to the projected changes in climate within the region. The power sector is vulnerable to projected changes in many dimensions of climate, including likely increases in the frequency and intensity of extreme weather events, higher air and water temperatures, changes in rainfall and river discharge patterns, and sea level rise. Climate change is expected to affect the entire electric power sector: fuel mining and production, fuel transportation to power plants, electricity generation, transmission through high voltage grids, and low voltage distribution to consumers. Patterns of energy load growth and end-use demand by consumers will also be altered by climate change. Given the rapidly increasing growth in energy use in the region and the large investments required in coming decades, attention must be given to ensuring a full accounting—and management—of risks to these investments related to climate change.

This report aims to highlight and raise awareness on the exposure and vulnerability of the energy sector in Asia and the Pacific to climate change. It also identifies adaptation options available to each source of energy generation as well as for the distribution and end use of electrical energy. The report does not aim to propose techniques and methodologies to assess and respond to exposure and vulnerability in specific settings. However, it is hoped that an increased awareness will be conducive to the development of such techniques and methodologies. A companion report, *Guidelines for Climate Proofing Investments in the Electric Power Sector,* provides a step-by-step approach to climate proofing investment projects in the sector. An explicit accounting of the impacts of climate change on existing energy infrastructure, energy project investments, and development planning in the energy sector are key to increasing the region's resilience to climate change and ensuring its continued economic development.

This report has been jointly produced by ADB's Regional and Sustainable Development Department and Southeast Asia Department, and is part of ADB's overall effort to provide technical resources to assist both its operational staff and its DMC partners in managing climate risks confronting their investment projects. These resources encompass guidance materials, technical notes, and case studies on integrating climate change adaptation actions and climate proofing vulnerable investments in critical development sectors.

Nessim J. Ahmad
Director, Environment and Safeguards (RSES)
Regional and Sustainable Development Department
Concurrently Practice Leader (Environment)
Chairperson, ADB Climate Change Adaptation and Land Use Working Group



Anthony Jude
Director
Energy Division
Southeast Asia Department
Co-Chair, Energy Community of Practice

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Pradeep Tharakan (climate specialist, Energy Division, Southeast Asia Department) initiated and provided guidance and technical advice for this report. Charles Rodgers (senior environment specialist [climate change adaptation], Regional and Sustainable Development Department) provided guidance and comments. The report also benefited from valuable comments and suggestions from Thomas Jensen (environment and energy specialist, UNDP Pacific Center, Fiji) and from peer reviews by Mr. Brian Dawson (senior climate change adviser, Secretariat of the Pacific Community, New Caledonia); Dr. Alberto Troccoli (head of the Weather and Energy Research Unit and leader of the Regional Weather, Climate & Energy Stream of the Commonwealth and Industrial Research Organisation's Marine and Atmospheric Research, Canberra, Australia); and the UK Met Office, Hadley Centre, UK. Throughout this effort, valuable support was provided by Lorie Rufo (environment officer [climate adaptation], Regional and Sustainable Development Department).

Abbreviations

ADB	Asian Development Bank
CO_2	carbon dioxide
CSP	concentrating (or concentrated) solar power
DMC	developing member country of the Asian Development Bank
FAO	Food and Agricultural Organization
IAEA	International Atomic Energy Agency
ICT	information and communication technology
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
MW	megawatt
MWh	megawatt-hour
OTEC	ocean thermal energy conversion
T&D	transmission and distribution

Glossary

Unless explicitly indicated otherwise, this glossary is a subset of the definitions presented in the glossaries of the Intergovernmental Panel on Climate Change (2007) and the contributions of its various working groups, as well as from the United Nations Framework Convention on Climate Change.

Adaptation. Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. There may be various types of adaptation:

> *Anticipatory adaptation.* Adaptation that takes place before impacts of climate change are observed; occasionally referred as proactive adaptation.
>
> *Autonomous adaptation.* Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems.
>
> *Planned adaptation.* Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.

Climate. Climate in a narrow sense is 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.

Climate change. Climate change refers to a change in climate over time, whether due to natural variability or as a result of human activity. The United Nations Framework Convention on Climate Change, 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."

Climate change impacts. The effects of climate change on natural and human systems. Depending on the state 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 has taken place.

Climate prediction. A climate prediction (or climate forecast) is the result of an attempt to estimate the actual evolution of the climate in the future (e.g., at seasonal, inter-annual, or long-term timescales).

Climate projection. The calculated response of the climate system to emissions or concentration scenarios of greenhouse gases, often based on simulations by climate models. Climate projections critically depend on the emissions scenarios used and therefore on highly uncertain assumptions of future socioeconomic and technological development.

Climate variability. Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) 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).

Downscaling. Downscaling is a method that derives local- to regional-scale (10 to 100 kilometers) information from larger-scale models or data analyses. There are two main methods: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods develop statistical relationships that link large-scale atmospheric variables with local and regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Extreme weather event. 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 or rarer than the 10th or 90th percentile of the observed probability density function.

General circulation models. General circulation models, or GCMs, representing physical processes in the atmosphere, ocean, cryosphere, and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. GCMs depict the climate using a three-dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere, and sometimes as many as 30 layers in the oceans. Only GCMs, possibly in conjunction with nested regional models, have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis.[1]

Impact assessment. The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of climate change on natural and human systems. Climate projections are used to first identify how the climate is changing, and then the impact of those changes on systems such as river basin dynamics are assessed, through hydrologic modeling, for example.

[1] From: www.ipcc-data.org/ddc_gcm_guide.html. Updated 11 November 2011, slightly edited.

Sensitivity. Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Special Report on Emissions Scenarios. The *Special Report on Emissions Scenarios* was a report prepared by the Intergovernmental Panel on Climate Change for the Third Assessment Report in 2001 on future emissions scenarios to be used for driving global circulation models to develop climate change scenarios. There exist four broad families of emissions scenarios (A1, A2, B1, and B2) that depend on different assumptions pertaining to economic growth, population growth, the adoption of new technologies, and the degree of integration among nations of the world.

Storm surge. The temporary increase, at a particular locality, of the height of the sea due to extreme meteorological conditions. The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.

Threshold. The level of magnitude of a system process at which sudden or rapid change occurs. The climate system tends to respond to changes in a gradual way until it crosses some threshold: thereafter any change that is defined as abrupt is one where the change in the response is much larger than the change in the forcing. The changes at the threshold are therefore abrupt relative to the changes that occur before or after the threshold and can lead to a transition to a new state.

Uncertainty. An expression of the degree to which the exact value of a parameter is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. Uncertainty can 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. Refers to 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.

Vulnerability assessment. A vulnerability assessment attempts to identify the root causes for a system's vulnerability to climate changes.

Executive Summary

While the electric power sector is generally a focus of attention in the context of discussions on greenhouse gas mitigation, the sector is itself vulnerable to projected changes in climate.

This publication, *Climate Risk and Adaptation in the Electric Power Sector*, focuses primarily on electric power generation, its transmission, and its distribution. The report aims to highlight and raise awareness of the exposure and vulnerability of the sector to climate change. It also discusses adaptation options available for each source of power supply as well as for the distribution of electric power. A second publication, *Guidelines for Climate Proofing Investments in the Electric Power Sector*, provides a step-by-step approach at a project level to assess climate risk and to climate proof investments in the sector.

Climate change impacts and the energy sector

There is unequivocal scientific evidence that the climate is warming and recent observed changes in the climate are very likely due to an increase in greenhouse gases produced by human activity. A recent assessment of the vulnerability of 193 countries to climate change rated 30 of these countries at extreme risk, of which 9 are ADB developing member countries (DMCs). The assessment excluded a number of ADB Pacific DMCs, many of which are also considered to be at extreme risk. A similar study ranked 14 DMCs as being at extreme risk from natural disasters and climate change.

The power sector is vulnerable to projected climate changes, including the following:

- Increases in water temperature are likely to reduce generation efficiency, especially where water availability is also affected.
- Increases in air temperature will reduce generation efficiency and output as well as increase customers' cooling demands, stressing the capacity of generation and grid networks.
- Changes in precipitation patterns and surface water discharges, as well as an increasing frequency and/or intensity of droughts, may adversely impact hydropower generation and reduce water availability for cooling purposes to thermal and nuclear power plants.
- Extreme weather events, such as stronger and/or more frequent storms, can reduce the supply and potentially the quality of fuel (coal, oil, gas), reduce the input of energy (e.g., water, wind, sun, biomass), damage generation and grid infrastructure, reduce output, and affect security of supply.
- Rapid changes in cloud cover or wind speed (which may occur even in the absence of climate change) can affect the stability of those grids with a sizeable input of renewable energy, and longer-term changes in these and precipitation patterns can affect the viability of a range of renewable energy systems.
- Sea level rise can affect energy infrastructure in general and limit areas appropriate for the location of power plants and grids.

Electric power in Asia and the Pacific is thus a vulnerable sector in a vulnerable region.

Table E1 provides a qualitative and indicative summary of expected impacts of climate change on various electricity production technologies, transmission and distribution (T&D) grids, and end-use demand. Extreme events such as cyclones can, of course, have serious impacts on power infrastructure and supply in general, beyond the impacts summarized in the table. While some of these impacts can cover a broad geographic area (e.g., changes in air temperature), others may be highly site-specific (e.g., changes in wind speed or water availability). Some columns of the table indicate typically "no significant impact," but as discussed in the main body of the report, on occasion impacts could be considerable. While Table E1 is only broadly indicative, it provides an initial approximation of the expected impacts of climate change and climate variability on the electric power sector. Particular areas of note include the following:

- Flooding is generally likely to have the biggest impact for a wide range of generation technologies.
- Higher water temperatures (where water is used for cooling purpose) generally have a more severe impact than higher air temperatures.
- Reduced availability of water can have limited to severe impacts, the more serious threats often related to insufficient cooling water.
- Hydropower output (though not necessarily infrastructure) can be severely affected by changes in precipitation.
- Geothermal power has relatively minor climate change sensitivities, mainly related to flooding.
- Although solar photovoltaic technologies have relatively minor climate change sensitivities, output varies with changes in cloud regimes, and concentrating and tracking solar technologies are

Table E1 Indicative Impacts of Climate Change on Electricity Generation, Transmission and End Use

Technology	Δ Air Temp	Δ Water Temp	Δ Water Availability	Δ Wind Speed	Δ Sea Level	Floods	Heat Waves	Storms
Coal	1	2	1-3	-	-	3	1	-
Oil	1	2	1-3	-	-	3	1	1
Natural gas	1	2	1-3	-	-	3	1	1
Nuclear	1	2	1-3	-	2a	3	1	-
Hydropower	-	-	1-3	-	-	3	-	1
Wind	-	-	-	1-3	3a	1	-	1-3
Photovoltaic	1	-	-	1	-	1	1	1
CSP/Solar tracking	-	-	2	2	-	1	1	2
Biomass/Biofuel	1	2	2	-	3a	3	1	-
Geothermal	-	1	-	-	-	1	-	-
Ocean	-	1	-	-	1	N/A	-	3
T&D grids	3	-	-	1	3a	1-2	1	2-3
End use	2	-	-	-	-	-	3	-

CSP = concentrating solar power, Δ = change in, T&D = transmission and distribution

[a] Higher severity in coastal or low-lying areas.

Notes: 3 = severe impact, 2 = medium impact, 1 = limited impact – = no significant impact, N/A = not applicable

Source: Modified and expanded from European Commission. 2010. *Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change.* Final report. European Commission Directorate-General for Energy Report EUR 24769.

vulnerable to damage from high-gusting winds and hail.

- Biomass generation shares climate change sensitivities with thermal generation technologies. In addition, biomass production is highly susceptible to climate change and the energy density of biomass can vary due to variations in photosynthetic/plant physiological interactions, often driven by CO_2 concentration changes.
- Ocean power technologies, currently not commercialized but with some promise for tropical coastal and island locations during the next 20–30 years, have varying sensitivities, with some technologies sensitive to changes in water temperature or sea level.
- T&D grids can be highly sensitive to high ambient temperature (increased electrical resistance) and storm damage.
- Electricity end-use demand is sensitive to temperature changes in general but particularly to heat waves.

Adaptation to climate change

Electric power investment decisions have long lead times and long-lasting effects, as power plants and grids often last for 40 years or more. This explains the need to assess the possible impacts of climate change on such infrastructure, to identify the nature and effects of possible adaptation options, and to assess the technical and economic viability of these options.

Adaptation measures can generally be divided into engineering and non-engineering options. In a number of circumstances, it may be best to promote no or low-risk adaptation strategies that deliver development benefits regardless of the nature and extent of changes in climate. This is a useful and practical approach wherever uncertainty is high regarding climate change, and where large climate-proofing capital investments cannot be easily justified. In other circumstances, such climate-proofing investments may be justified. On the other hand, a "do nothing" response may occasionally be more appropriate and cost-effective.

Engineering adaptation measures include the following:

- In general, more robust design specifications could allow structures to withstand more extreme conditions (such as higher wind or water velocity) and provide them with the ability to cope safely with higher air and/or water temperatures. In some circumstances, it may also be necessary to consider relocating or refitting extremely vulnerable existing infrastructure. Furthermore, decentralized generation systems may reduce the need for large facilities in high-risk areas and minimize climate risk. Finally, the reliability of control systems and information and communications technology (ICT) components may improve from redundancy in their design and from being certified as resilient to higher temperatures and humidity.
- For thermal power, enlarged or retrofitted cooling systems (including air cooling) where water is expected to be increasingly scarce may be considered; where increased flooding is expected, designing facilities to be waterproofed may be an option.
- For nuclear power, redundant cooling systems may be considered, and it may be possible to assure robust protection from floods, tsunamis, or other extreme events that can otherwise damage backup generation and essential cooling systems.
- For hydropower, where water flows are expected to change over the life of the system, it may be possible to consider diverting upstream tributaries, building new storage reservoirs, modifying spillways, and installing turbines better suited to expected conditions. Greater water flows (whether from glacial melting or increased precipitation) may require higher and more robust dams and/or small upstream dams.
- Where wind speeds are likely to increase, it may be possible to design turbines and structures better able to handle higher wind speeds and gusts, to capture greater wind energy with taller towers, or to design new systems better able to capture the energy of increased wind speeds.
- For solar photovoltaic systems, where temperature increases or significant heat waves

are expected, it may be useful to consider designs that improve passive airflow beneath mounting structures (reducing panel temperature and increasing power output); to specify heat-resistant cells, modules, and components; and to consider distributed systems to improve grid stability and micro-inverters (for each panel) to improve both output and grid stability where cloud cover fluctuates rapidly (e.g., with higher winds).

- For solar concentrating or sun-tracking systems, where higher wind speeds, more intense storms, and gusts are likely, it may be necessary to consider more robust structures, tracking motors, and mountings, and to consider air or waterless cooling in water-restricted areas.
- For biomass/biofuels, in addition to adaptations for thermal systems in general, more robust feedstock may be designed (e.g., tolerant to heat, salt, or water), and it may be possible to expand or introduce more efficient irrigation systems, depending on expected climatic changes.
- For geothermal, specifications might require greater protection where floods are likely to increase. Where cooling water is reduced with climate change, it may be possible to substitute air-cooled systems, although it may be less expensive to develop new water sources.
- For ocean power, only sea wave and tidal power generation are approaching commercial viability. It may be possible to specify the ability of systems to withstand extreme (100-year) waves or alternatively specify designs that are sufficiently inexpensive that the financial loss from destruction is less than preventative measures. For sea wave power generation, floating systems may be climate proofed with protection mechanisms against storm surges (e.g., automated lowering of expensive components to the sea floor, designs that can cope with extreme conditions, or mechanisms to disconnect or shut down during extreme events).
- For T&D (including substations), specifying redundancy in control systems, multiple T&D routes, relocation, and/or underground distribution for protection against wind, high temperatures, corrosion, and flooding may be considered. Where stronger winds are expected, higher design standards for distribution poles may be adopted. Where temperatures are likely to increase, more effective cooling systems for substations and transformers can be put in place.
- For electricity end use, adaptation measures to cope with increased demand with temperature rises are of three types: (i) increasing generation (MWh) and capacity (MW) to meet the higher demand (business as usual approach); (ii) improving the efficiency of power supply (generation, transmission, distribution system improvements); and (iii) improving end-use efficiency for buildings, facilities, and energy-intensive appliances and machinery, thus requiring less investment in generation and distribution.

Non-engineering adaptation measures include the following:

- In general (including generation technologies not listed below), it may be cost-effective to put in place more robust operational and maintenance procedures, improved and better coordinated land use planning (e.g., rezoning land use so future power infrastructure is in less vulnerable areas), policies and enforceable regulations to improve energy security, decentralized local planning and generation, integration of adaptation and mitigation planning, integration of climate change and disaster management planning, improving forecasting of demand changes and supply–demand balance with climate change, integrating power sector planning with that of other sectors (including water supply), and improving localized models used to predict storms and flood hazards. It may be of interest to set up rapid emergency repair teams to repair damaged facilities quickly.
- For nuclear power, it may be appropriate to develop more stringent safety regulations against extreme events, including flooding.
- For hydropower, new operating rules, improved hydrologic forecasting, and coordinating power planning and operations with other water-use projects may be useful. For existing hydro infrastructure, localized regional climate modeling might suggest operational changes to optimize reservoir management and improve energy output by adapting to changes in rainfall or river flow patterns. Basin-wide management strategies that

take into account the full range of downstream environmental and human water uses may prove necessary. Restored and better-managed upstream land, including afforestation to reduce floods, erosion, silting and mudslides, may provide useful protection to existing infrastructure.
- For wind power, it may be possible to choose sites that take into account expected changes in wind speeds, storm surges, sea level rise, and river flooding during the lifetime of the turbines.
- For solar photovoltaic power, it may be possible to select locations where expected changes in cloud cover, airborne grit, snowfall, and turbidity are relatively low.
- For solar concentrating or tracking systems, avoiding locations with high, gusting winds or expectations of increased cyclones/extreme events may be an option.
- For wind and solar technologies, it may be possible to improve the reliability of expected output with better weather predictions.
- For biomass/biofuels, early warning systems for rainfall and temperature anomalies, emergency harvesting arrangements for an imminent extreme event, and provision of crop insurance can be appropriate options.
- For T&D, new mandatory design codes for lines, transformers, and control systems may be adopted to cope effectively with the expected changes.
- For electricity end use, mandatory minimum energy performance standards for buildings, manufacturing facilities, and energy-intensive appliances can increase resilience of the sector.

The measures described above provide general guidance regarding possible adaptation measures for various climate sensitivities. However, detailed local assessments are necessary to provide greater confidence in understanding current climate variability and how the climate might change in the future, and therefore which measures are warranted at the level of specific projects. There is a need to improve energy sector (and broader) decision making by improving local weather and climate knowledge, regardless of whether large climate changes are expected; by improving access to existing meteorological and hydrological data; and by developing better mechanisms so that local weather and climate data are archived for the public good.

In some countries in Asia and the Pacific, there are broad policy intentions to begin integrating climate change considerations within electric power planning and policy. However, thus far there is little detail on methods and approaches to evaluate risk and develop practical action plans. For this purpose, it is important to significantly improve coordination and planning among key energy agencies, other government ministries (e.g., finance, environment, disaster management), energy producers, regulators, governments, and users to cope with climate-induced stresses, which are expected to become significant.

Introduction

Energy has been a key area of Asian Development Bank (ADB) support to its developing member countries (DMCs). Over the period 1967–2010, this support reached $33.0 billion in cumulative loans (representing 20% of all ADB loan finance) and $651 million in grants (representing 10% of all grant assistance). In 2010, energy sector loans totaled nearly $2.5 billion, more than 70% of which (about $1.8 billion) was support for clean energy initiatives (ADB 2011). By 2013, ADB's clean energy loans, meant to improve energy security and facilitate a transition to low-carbon economies, are likely to surpass $2 billion. Historically, electricity has dominated ADB energy sector assistance. Over the period 1990–2006, loans to improve electric power production, distribution, efficiency, and security totaled $27.9 billion, compared with $2.7 billion for oil and gas (ADB 2009).

Between 2005 and 2030, primary energy demand in Asia and the Pacific is expected to grow by 2.4% per year (ADB 2009a) or more.[2] Electricity demand is projected to increase more rapidly, at an average annual rate of 3.4%, with DMCs accounting for 86.5% of the total increase. In 2030, fossil fuels are expected to provide more than 71% of DMC electricity generation, led by coal (54.8%) and gas (15%) with oil accounting for only 1.6%. Hydropower (12.5%) and nuclear (12%) are expected to provide far more electricity than non-hydro renewable energy technologies (including solar, wind, geothermal, and biomass, with a total of 4.1%) although these will grow rapidly from a very low base of 0.8% in 2005 (ADB 2009a). The People's Republic of China and India together accounted for 43.8% of global coal-fired power generation in 2010; this is projected to rise to 57% by 2030 (Refocus 2011).

ADB projections indicate that electricity use in DMCs in 2030 will be about 2.3 times that of 2005. Projections over several decades are inevitably imprecise. Although the rates of change in generation technologies and fuel mixes are highly uncertain, energy demand in Asia is projected to grow rapidly; energy supply will remain a key area of ADB's support for some decades, and coal will continue to dominate fuel use for power generation.

The investments required to meet this level of demand will be substantial. The Asia Pacific Energy Research Center (APERC 2009) estimates that the electricity and heat industry in the Asia–Pacific Economic Cooperation

[2] A more recent report indicates a higher expected rate of growth in Asia's energy demand, 3.4% annually from 2000 to 2030 (ADB 2011a). However, the earlier report has more detailed coverage of future DMC energy demand overall and electric power. The differences in assumed growth rates do not affect the analysis or conclusions of this report.

(APEC) region will require between $6,400 and $8,700 billion from 2006 through 2030 (in constant 2006 US dollars). Asia is expected to account for about $3,300–4,600 billion, or more than 50% of the total. Of this, about 65% is required for generation, 25% for transmission, and 10% for distribution.[3]

Electric power production and distribution infrastructure can be highly vulnerable to the impacts of climate change. Sea level rise, more frequent and intense storms and storm surges, increased wave heights, changes in patterns of cloud cover and wind speeds, floods, droughts, and temperature changes can all have consequences for the design, construction, location, and operations of power infrastructure. These impacts will vary considerably across generation technologies. Inadequate attention to these impacts can increase the long-term costs of electric power sector investments, the likelihood that they will not deliver intended benefits, and the probability of failure under climate stress.

Power generation plants and distribution networks typically operate for several decades. Systems built in the next few years should therefore account for the possible impacts of climate change and be designed, sited, and operated to be either adapted (at the outset) or adaptable (in the future) to potential climate change. This applies equally to fossil-fuel power systems; hydropower, which can be extremely vulnerable to climate change; nuclear power; and clean renewable energy, which is likely to account for a large and increasing share of ADB's energy sector loans.

This publication, *Climate Risk and Adaptation in the Electric Power Sector*, aims to highlight and raise awareness of the exposure and vulnerability of the electric power sector to climate change. It also discusses adaptation options available for each source of electric power supply as well as for the distribution and use of electrical energy. A second publication, *Guidelines for Climate Proofing Investments in the Electric Power Sector*, provides a step-by-step approach at a project level to assess climate risk and to climate proof investments in the sector.

Each electric power sector study or investment is conceived with particular technical, economic, social, and environmental objectives at a specific location within a political context and specified time frame. Although this publication aims to provide guidance on the likely climate change impacts on various electric power technologies and appropriate adaptation responses, some aspects of particular technical assistance or investment projects will be site-specific or country-specific, possibly with additional—or fewer—areas of likely impact. The report discusses impacts that are expected to affect electric power production and use, as well as adaptation options that could usefully be incorporated into terms of reference for development of policies, plans, and regulations for preliminary project studies and for detailed engineering designs, but they are not comprehensive. For the technologies discussed here, more details can be found in the documents presented in the list of references.

Part II presents a detailed discussion of the possible impacts of climate change on the electric power sector and the nature of the adaptation options available. Part III discusses issues pertaining to mainstreaming adaptation into electric power sector development policy and planning.

[3] The *World Energy Outlook 2011* (IEA 2011) estimates a global energy sector investment requirement in 2011–2035 of $38,000 billion in 2010 dollars, of which two-thirds is outside of OECD member countries. Of the total, 45% is expected to be for the electric power sector, of which 60% is for generation and 40% for T&D.

Climate Change and the Electric Power Sector

A. The Case for Action

There is strong scientific consensus that climate change is happening and that this is mostly due to anthropogenic activities. In early 2007, the Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report. In the report, the IPCC noted that over the past 150 years, global average surface temperature had increased by 0.76°C, and that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic (human) greenhouse gas concentrations.[4] The World Meteorological Organization (WMO 2011) has reported that 2010 tied for the warmest year on record since 1880, with an estimated average global temperature 0.53°C ± 0.09°C above the 1961–1990 average of 14°C, and that the decade 2001–2010 was the warmest on record. The evidence of a warming world is not restricted to the temperature record; changes in precipitation patterns, increases in the frequency and/or intensity of extreme weather events, and a rise in mean global sea levels have all been observed in the recent past. Looking into the future, the IPCC (2007) concluded that world temperatures may rise by between 1.1°C and 6.4°C during the 21st century (relative to the period 1980–1999),[5] depending on the emissions scenario that is realized (the "best estimate" range is between 1.8°C and 4.0°C). More recent assessments suggest that temperatures may be higher than those estimated by the IPCC (Potsdam Institute 2008, World Bank 2010, and Norden 2010).

Changes in climate, such as higher temperatures and sea level rise, may result in consequences such as the following:

- Increases in water temperature (both gradual and extreme) are likely to reduce electric power generation efficiency, especially where water availability is affected.
- Increases in air temperature will reduce generation efficiency and output and increase customers' cooling demands, stressing the capacity of generation and grid networks.

[4] In the language of the IPCC, "very likely" stands for "with a probability greater than 90%."

[5] More precisely, 1.1°C is the lower bound estimate of the range of likely increase under the B1 emissions scenario, while 6.4°C is the upper bound estimate of the range of likely increase under the A1FI emissions scenario (IPCC 2007).

- Changes in precipitation patterns and surface water discharges as well as an increasing frequency and/or intensity of droughts or floods may adversely impact hydropower generation and affect water availability for cooling purposes to thermal and nuclear power plants. Climate change may also affect competition for water availability by other sectors.
- Extreme weather events, such as stronger and/or more frequent storms, can reduce the supply and sometimes quality of fuel (coal, oil, gas), reduce the input of energy (e.g., water, wind, sun), damage generation and grid infrastructure, reduce output, and affect security of supply.
- Rapid changes in cloud cover or wind speed (e.g., gusts) can affect the stability of those grids that have a sizable input of renewable energy, and longer-term changes in these and precipitation patterns can affect the viability of a range of renewable energy systems.
- Sea level rise can affect electric power sector infrastructure in general and limit the choice of location of power plants and grids, which are often in low-lying areas.

The electric power sector can be highly vulnerable to projected changes in climate variables, as further illustrated in Box 1 for Ho Chi Minh City in Viet Nam.

A climate change vulnerability index prepared by the global risks advisory firm Maplecroft assessed the vulnerability of 193 countries to climate change, considering exposure to climate-related natural disasters and sea level rise, human sensitivity, and the adaptive capacity of the government and infrastructure to combat climate change (Maplecroft 2012). Nine of the 30 countries categorized as "extreme risk" are DMCs: Bangladesh (2), Cambodia (6), Philippines (10), Nepal (13), Myanmar (20), Viet Nam (23), Papua New Guinea (25), Indonesia (27), and India (28).

A similar study ranked 14 DMCs at extreme risk from natural events and climate change. Among the 10 countries most at risk, 7 are DMCs; among the 15 countries most at risk, 10 are DMCs (BündnisEntwicklungHilft 2011). These (from worst to least affected) are Vanuatu, Tonga, the Philippines, Solomon Islands, Bangladesh, Timor-Leste, Cambodia, Papua New Guinea, Brunei Darussalam, and Afghanistan.

Box 1 Vulnerability of the Electric Power Sector in Ho Chi Minh City

Two of Ho Chi Minh City's power plants (Phu My and Hiep Phuoc) fall within the projected flood zone, even with flood control measures in place, and may be exposed to extreme floods by 2050. A third thermal plant (Thu Duc) is only 0.1 km away and its operations could also be disrupted directly or through loss of cooling water. Ho Chi Minh City's transmission and distribution (T&D) networks could be affected by inundation of water; high winds and storms; and increased humidity, temperature, and salinity. Power lines designed to withstand winds of 30 meters per second have already been extensively damaged during storms. Flooding can affect aboveground lines and substations. Increased humidity can increase the risk of corrosion of steel infrastructure. Salt accumulation in soils and increased dryness and hardness of soils surrounding underground T&D cables can cause corrosion problems and increase transmission losses.

Many electricity substations and transmission lines are also within or close to areas where extreme flooding events are predicted for 2050 and are at risk of damage. All six existing and all four planned 500 kilovolt (kV) substations are at high risk, as are many high voltage (500 kV) transmission lines.

Finally, projected temperature increases by 2050 in Ho Chi Minh City are likely to lead to increased power demand and lower generation and transmission efficiency.

Source: Asian Development Bank. 2010. *Ho Chi Minh City: Adapting to Climate Change.* Summary report. Manila.

Cities as well as countries have been assessed for climate change vulnerability. Of the world's 20 fastest-growing cities, six have been classified as "extreme risk": Kolkata, Manila, Jakarta, Dhaka, and Chittagong (Maplecroft 2012). An additional 10 cities globally rated as "high risk" include Guangdong, Mumbai, Delhi, Chennai, and Karachi. In a recent study, Brecht et al. (2012) estimated that 19 of the 25 most exposed urban populations to sea level rise and storm surges were located in DMCs; all 10 most exposed urban populations in the world are estimated to be located in this region.

The majority of ADB's 14 Pacific DMCs are also believed to be in a high risk or extreme risk category.[6]

As shown in Figure 1 (upper), there has been a doubling in the number of natural catastrophes globally over the course of the last 30 years, although not all of these are climate related. Financial losses in 2010 values increased by a factor of 3.8 during the same period globally, but the change in the Asia–Pacific region could differ.

According to Munich RE (Raloff 2012), the trends shown in Figure 1 (lower) provide strong evidence that climate change is already impacting human suffering and the world's economies, although the climate change impacts cannot be isolated with precision.

Asia and the Pacific is thus projected to experience significant impacts from climate change. Within this region, the electric power sector is highly sensitive to changes in climate. Given the rapidly increasing growth in energy use in the region, and the large investments required in coming decades, attention must be given to ensuring that these investments are made while fully accounting for projected climate change. The next section discusses in more detail the vulnerability of the various electric power supply sources and the nature of adaptation options.

B. Vulnerability of the Electric Power Sector to Climate Change and Options for Adaptation

Much of the Asia–Pacific electric power infrastructure is located where weather and climate are expected to be increasingly variable (IPCC 2012), such as areas that are flood prone, low-lying, drought prone, and highly exposed to severe storms.

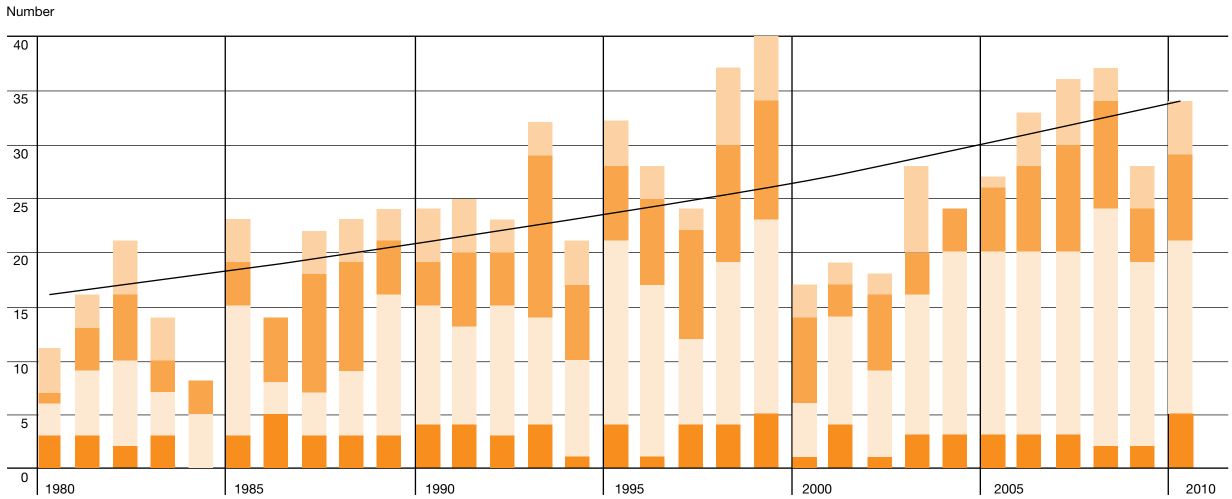
Climate change is expected to affect the entire sector, including fuel mining or production, fuel transportation to power plants, electricity generation, high voltage transmission through grid networks, and low voltage distribution to consumers. Patterns of energy load growth and end-use demand by consumers will also be altered by climate change. Vulnerability to projected changes and options for adaption are discussed below for each of these components of the electric power production and supply chain.

Technically, it is generally feasible to adapt effectively to the possible impacts of climate change over short-, medium-, and long-term periods. Much of the electric power infrastructure is already designed and built with a significant degree of flexibility and resilience, at least regarding the short term. However, electric power is not an isolated system: energy, transport, and water infrastructure tend to be highly interconnected with each other and with information and communications technology (ICT), which increasingly monitors and controls electricity operations. Climate change impacts on power systems can seriously affect water and transport, and vice versa, with complex and cascading impacts. Understanding the vulnerability of these interactions to climate change and the potential effects of multiple hazards is critical for the energy sector (URS 2010).

[6] A set of 15 peer-reviewed reports released in November 2011 on vulnerability and climate change projections for ADB's Pacific DMCs prepared by the Commonwealth Scientific and Industrial Research Organisation is available from the Pacific Climate Change Science Programme at www.cawcr.gov.au/projects/PCCSP.

Figure 1 Natural Catastophes and Financial Losses, 1980–2010

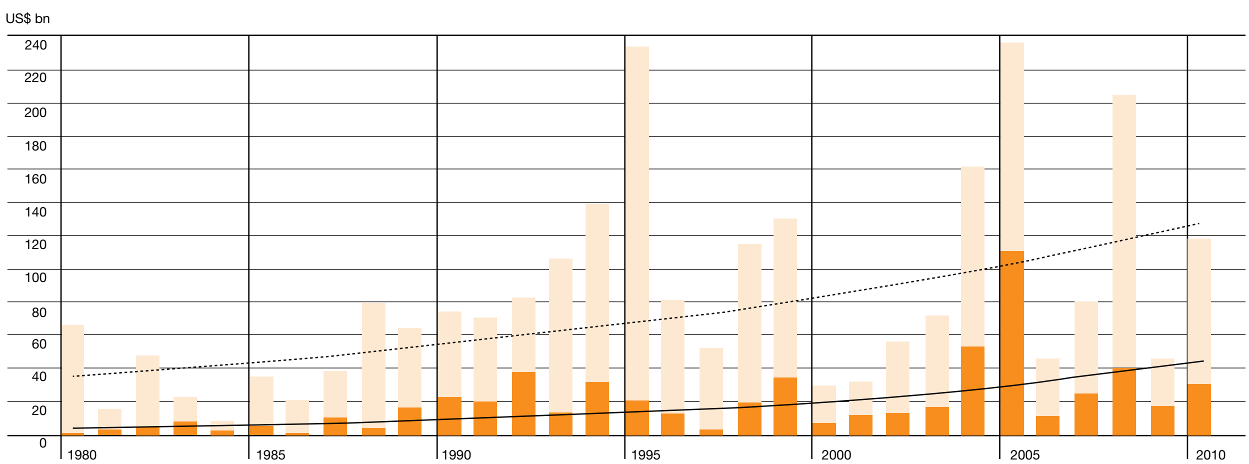
Number of events



The chart shows for each year the number of “great” and “devastating” natural catastrophes since 1980, divided up by type of event.

- Geophysical events: Earthquake, volcanic eruption
- Hydrological events: Flash flood, river flood, storm surge, mass movement (landslide)
- Meteorological events: Tropical storm, winter storm, severe weather, hail, tornado, local storms
- Climatological events: Heatwave, freeze, wildland fire, drought
- Trend

Overall losses and insured losses—Absolute values and long-tem trends



The chart presents the overall losses and insured losses for “great” and “devastating” natural catastrophes- adjusted to present values.

- **Overall Losses (in 2010 values)**
- **Of which insured losses (in 2010 values)**
- **Trend: Overall losses**
- **Trend: Insured losses**

Source: Munich Re. 2011. Natural Catastrophes 2010: Analysis, Assessments, Positions. Asia Version.

Adaptation to climate change is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (GIZ 2011). Decision makers need to understand the limitations of climate projections before integrating these data into adaptation processes. In situations of high uncertainty, it may often be an appropriate response to implement design or operational changes that make sense even if climate conditions were assumed not to change (or change minimally).

Many vulnerability management and adaptation responses require appropriate development policies, especially economic policies, that often lie outside the energy sector decision-making framework but nonetheless are important determinants on the energy sector. Adaptation measures specific to the electric power sector can generally be divided into engineering (design) specifications (e.g., safe temperature and humidity limits for generation plant and components, higher wind and seismic stresses, redundancy in control systems, multiple transmission routes) and non-engineering options (e.g., revised operational and maintenance procedures, land use planning, flood control, policies and regulations to improve energy security, minimum energy performance standards for buildings and appliances). In some specific circumstances, a “do nothing” response, such as allowing infrastructure to deteriorate and be decommissioned instead of climate proofed, may also be appropriate.

Some adaptation options for climate change on electricity systems are illustrated in Box 2 for Ho Chi Minh City, which is already at serious risk of flooding, both from regular and extreme climatic events such as tropical storms and typhoons and from likely future increases in ambient temperature. The vulnerabilities of electricity supply in Ho Chi Minh City and options for adaptation are common to many DMCs and are discussed in greater detail in the following sections.

Box 2 Adaptation Options for the Electric Power Sector in Ho Chi Minh City

For Ho Chi Minh City, adaptation measures are required to protect the availability of power resources, allow efficient operations, and accomodate expected changes in seasonal patterns of demand. These include the following:

- Dong Nai River Basin hydropower, an important part of Ho Chi Minh City’s supply, may require structural changes to safeguard generation capacity. These may include diverting upstream tributaries, new storage reservoirs, modifying spillways, and changing the numbers and types of turbines. Non-structural options may include new operating rules, improving hydrologic forecasting, better coordinating of power operations and coordination with other water-use projects.
- Existing high-risk infrastructure may be retrofitted for protection against storms, flooding, and increased salinity and temperature, and relocated where necessary. Transmission and distribution lines may require relocation and revised design codes for protection against wind, high temperatures, corrosion, and flooding. Estimating the costs and benefits of retrofitting cooling systems could indicate the economic efficiency of such climate-proofing investments. Relocation or refitting of extremely vulnerable infrastructure may also need to be considered.
- A broader mix and balance in generation option can improve energy security and stability of supply. Options include decentralized renewable energy, decentralized planning and generation, integration of adaptation and mitigation planning, forecasting demand changes with warming and improving supply-side management, integrating power planning with that of other sectors, and rezoning land use so future energy infrastructure is in less vulnerable areas.

Source: Asian Development Bank. 2010. *Ho Chi Minh City: Adapting to Climate Change.* Summary report. Manila.

1. Fossil Fuel Production and Transport

Vulnerability of Fossil Fuel Production and Transport to Climate Change

Coal is expected to be the main fuel for Asia's electricity production for the next several decades. Coal mine operations require a considerable volume of water to allow discharges into rivers from open pits without breaching water quality regulations. However, too much water (e.g., rainfall) can degrade the quality of coal stockpiles by increasing its moisture content and can affect coal output and transport through flooding. Some recent impacts of heavy rain on coal are summarized in Box 3.

The effects of hurricanes or other extreme events on oil extraction are well known. During Hurricane Katrina in 2005, more than 100 oil and gas platforms in the Gulf of Mexico were destroyed or damaged, causing US fuel prices to rise by 38%[7] (Acclimatise 2009, Rueben and Hoo 2005). Hurricane Alicia in 1983 affected US Gulf Coast refinery output for more than a year, and in 2010 oil refineries in Pakistan shut down due to flooding. The force of extreme weather events can dislodge underwater pipelines from the seabed and cause structural damage to pipelines, including dents, kinks, and separation from risers (Neumann and Price 2009).

Climate change impacts on oil and gas facilities vary depending on their location (Cruz 2010):

Box 3 Effects of Heavy Rain on Coal Production

Heavy rains frequently disrupt coal production and transport, as illustrated by the following examples:

- Record rains and heavy floods during La Niña weather patterns in late 2010 to early 2011 in Australia closed coal mines and buried rail lines in mud, reducing production for months, running down stocks and substantially raising fuel prices for Asian and local buyers. As heavy rains were expected in late 2011 and early 2012, one large mine is building a new bridge and completing a new levee designed for a 1-in-1,000 year flood event (replacing one designed only for a 100-year flood) to prepare for the eventuality that these conditions become more typical.
- In Indonesia, heavy rains and flooding in Kalimantan in late 2010 to early 2012 shut down mines, reduced output, and damaged coal transport. Coal production in the Kalimantan region is often hampered during the December through March monsoon season, with miners banking on the dry season to catch up on production. There have been concerns that changing weather patterns may spread rain more equally throughout the year, with no dry season to make up for wet season losses.
- In the Democratic People's Republic of Korea, heavy rainfall in July 2010 submerged 150 cutting faces of more than 30 coal mines, washed away hundreds of thousands of tons of coal from some 40 coal yards, caused pumping equipment failure due to lack of electricity, and stopped transport as bridges and rail lines were damaged by landslides. The government reported that the downpours seriously affected the nation's coal output, transport, and electricity production.
- There are concerns that wetter climates may increase the frequency or duration of such disruptions.

Sources: Behrmann, E. and J. Riseborough. 2011. *Record Coal Price Risk Gaining on Australian Rain.* Bloomberg, 12 October; Fickling, D. 2011. Floods to impact coal markets for months. *Dow Jones Newswires*. 6 January; MLC Investment Management (MLC). 2011. Extreme Weather Takes a Toll. *MLC Viewpoint*. March; and Sharples, B. and Y. Rusmana. 2010. *No Gain From Rain for Indonesia Coal as China Demand Cools: Energy Markets.* Bloomberg. 6 August.

[7] Katrina struck in late August 2005. Between June 27 and September 6, the average US retail price of gasoline rose from \$2.22 to \$3.07 per gallon, an all-time high in both real and nominal terms. The rapid increase was attributed to the hurricane (Rueben and Hoo 2005).

- Low-lying coastal areas such as Jamnagar, India, and Jurong Island, Singapore, which contain critical oil and gas facilities, could face increased coastal flooding, storm surges, sea level rise, ground subsistence, erosion, and changing precipitation patterns that may affect water supply.
- Any areas subject to changes in atmospheric temperature could face water scarcity problems.
- Arctic areas, where permafrost is expected to melt, can face severe disruptions to oil and gas extraction and their transportation infrastructure.

Although pipelines are generally the preferred and safest method of transporting oil and gas, they can be vulnerable to flooding resulting in soil erosion and exposure, which are especially damaging to valves, pump stations, and equipment at river crossings (Cruz 2010).

Adaptation Measures for Fossil Fuel Production and Transport

Engineering adaptation measures for fossil fuel mining (coal) or production (oil and gas) could require improving the robustness of the engineering designs and operations of installations, particularly those offshore that are highly vulnerable to storms. For opencast and underground mines, construction or augmentation of reservoirs can reduce the risks of flooding and water shortages. Structural measures such as dykes, berms, and spillways can protect against flooding, salinity, and other storm events (WWF undated).

New and existing mining developments could include improved flood hazard assessments. Other options include reassessing flood-prone areas and elevating buildings or vulnerable components above the 100-year flood contour level (Cruz 2010); flood-proofing buildings; and adopting techniques that slow, steer, and block water flows. Where practical, future mines can be sited where the exposure to flooding or drought risk is reduced. Power plants and pumps should preferably be sited where there is an adequate supply of cooling water, and air cooling should be considered as an alternative to water cooling (Michaelowa et al. 2010). Oil and gas pipelines can be designed to be more structurally flexible to cope with both soil subsidence and higher temperatures and storms.

An important non-engineering adaptation approach for fossil fuel extraction is improving the capacity of models to predict storms and map their tracks more accurately. This could significantly reduce storm impact on oil and gas operations (Froude and Gurney 2010), particularly offshore extraction and pumping, as there would be more time to prepare.

Some key climate change impacts on fossil fuel extraction and transport, along with adaptation options, are summarized in Table1.

2. Power Generation

2.1. Thermal Power (Coal, Oil, and Gas)

Vulnerability of Thermal Power Generation to Climate Change

Climate change can affect the output, efficiency, and financial viability of electricity generation. Despite rapid growth rates of renewable energy, thermal sources are expected to account for nearly 80% of primary energy use in Asia and the Pacific in 2030—with coal contributing about 38%, oil, 27%, and natural gas, 15%—and thermal generation for 70% of electricity supply (ADB 2009a). Addressing adaptation options for thermal power is thus particularly important.

An increase in ambient temperature results in a decrease in the difference between ambient and combustion temperature, reducing the efficiency of gensets, boilers, and turbines (Contreras-Lisperguer and de Cuba 2008, Wilbanks et al. 2008). This is also true for air-cooled systems. While the reduction in efficiency may be relatively small for coal-fired plants, it is measurable. For gas turbines, the reduction in power output is proportional to temperature increase: it is estimated that an increase of 5.5°C in ambient air temperature may reduce output by approximately 3% to 4% (Neumann and Price 2009, Acclimatise 2009). This is important, as Asian DMCs may use nearly

Table 1 Key Climate Change Impacts and Adaptation—Fossil Fuel Extraction and Transport

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Temperature increase	• Oil and gas pipelines	• Damage by melting permafrost (as soil subsidence threatens structural integrity).	• More robust and structurally flexible pipeline designs
Precipitation increase; flooding	• Coal mining • Coal storage • Coal transport	• Reduced coal quality (higher moisture content of opencast mining) • Increased coal availability (e.g., if coal seam fires are extinguished) • Reduced output (if floods affect mines) or availability (if floods affect transport)	• Build or enlarge reservoirs to reduce flooding risk • Build dykes, berms, and spillways • Carry outflood hazard assessments • Relocate fuel storage away from flood-prone areas
Drought or precipitation decrease	• Coal and oil • Mine air conditioning equipment • Drilling equipment	• Reduced coal availability (less water for mine air conditioning and operations); higher probability of seam fires • Reduced shale oil or gas availability (very large water demands for drilling and removing drilling mud)	• Build or enlarge reservoirs to reduce water shortages • Develop/reroute water sources
Storm strength and/ or frequency increase	• Coal • Oil • Mining equipment • Oil platforms	• Reduced coal production (if storms affect opencast excavation equipment) • Reduced oil production (if storms affect coastal or offshore oil platforms)	• Improve robustness of designs, particularly offshore • Build/improve dykes, berms, and spillways onshore • Improve models used to predict storms.

Sources: European Union (EU). 2011. *Impacts of Shale Gas and Shale Oil Extraction on the Environment and on Human Health*. European Parliament Directorate-General; Michaelowa et al. 2010. Use of Indicators to Improve Communication on Energy Systems Vulnerability, Resilience and Adaptation to Climate Change. In A. Troccoli (ed.). *Management of Weather and Climate Risk in the Energy Industry.* Dordrecht (The Netherlands); and Neumann, J. and J. Price. 2009. *Adapting to Climate Change: The Public Policy Response: Public Infrastructure*. Resources for the Future Climate Policy Program. June.

10 times more gas than oil for power generation in 2030 (ADB 2009a). For combined cycle gas turbines, a recent British study suggests that a 5°C average temperature increase during summer would result in only a 0.34% efficiency drop (URS 2010).

Simulations of water management for a thermal plant in Germany also suggest that increasing average air and water temperatures result in only small changes in gross electrical output until 2050. A more serious issue is likely to be access to sufficient water for cooling and returning it to the source at a temperature low enough to prevent damage to aquatic ecosystems (Greis et al. 2010). The volume of water required for fuel processing, cooling, and power production can be considerable (FMENCNS 2007, NWF 2011, DHI Group 2008). Fossil fuel-fired thermal power stations have high water requirements, the volume depending on both generating technology, cooling technology, and capacity in megawatts (MW) (Mima and Criqui 2009).

Box 4 summarizes the expected climate change impacts of a planned thermal power plant in Viet Nam and the likely costs of inaction.

Adaptation Measures for Thermal Power Generation

Where climate change results in reduced availability of cooling water, power stations can be designed to withdraw less water from the source and consume less water internally. Cooling water is either used once (open-loop or once-through) or recovered and

Box 4 Climate Change Threats to the O Mon IV Thermal Power Plant in Viet Nam

In 2010, a rapid climate change threat and vulnerability assessment was undertaken for ADB on a (then) proposed combined cycle thermal power plant in Viet Nam, approved for ADB funding support in November 2011.
The most significant potential climate change threats were estimated to be rising air and river water temperatures.
The assessment projected air temperature to rise by 2.8°C–3.4°C over the period of analysis. As for water temperature, it was projected that the proportion of the year when river water temperature is at or above the design temperature of 29.2°C could significantly increase.

The components most vulnerable to reduced performance are the gas and steam turbines, the air compressors, and the circulating water pumps. Most other components are expected to have minor vulnerability to climate change. Asset damages (possibly resulting from river bank erosion and floods) are not projected to be of significance.

The study showed that the power plant, as currently designed, may experience an aggregate loss in power output of approximately 827.5 GW as a result of projected increases in air and water temperature over the period 2015–2040. This corresponds to approximately 0.8% of its total design power output over that same period. In addition, the reduction in net efficiency will result in a relative increase in fuel consumption. In present value terms, the loss of power output and increased fuel consumption are estimated to cost approximately $11.0 million over the period 2015–2040. These numbers, in the context of this specific power project, were deemed to be relatively small. Analysis conducted on other thermal plants in the region could yield different results.

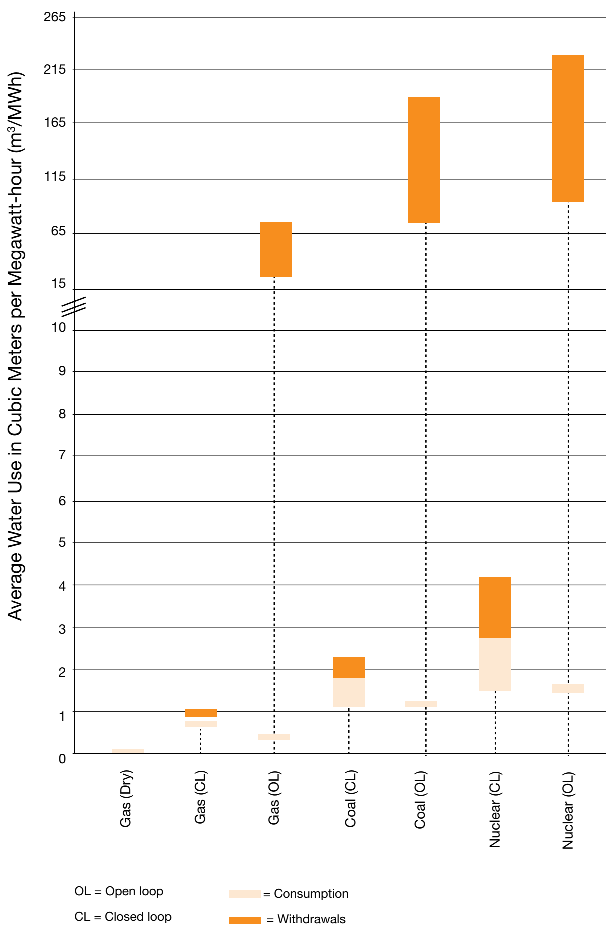
Source: International Centre for Environmental Management (ICEM). 2010. *O Mon IV Power Plant: Rapid Climate Change Threat and Vulnerability Assessment*. Prepared for Asian Development Bank. Ha Noi, Viet Nam.

returned to its source (closed-loop or recirculating). Recirculating systems can use water in cooling ponds or towers or use dry air instead of water (WEC 2010). Although an open-loop system can withdraw 20–200 times as much water from rivers or other sources as a recirculating system (Figure 3), the latter may consume considerably more water due to losses through evaporation. Nonetheless, environmental regulations that limit the discharge temperature of hot water back into surface waters to protect aquatic life can drive the choice toward closed-loop recirculating systems, increasing overall water use (WEC 2010). Wet closed-loop cooling systems have an installation cost approximately 40% higher than once-through systems; dry cooling systems use little or no water but are 3 to 4 times more expensive than wet recirculation. In comparison to open-loop wet systems, a closed-loop system with a cooling tower decreases power efficiency by up to 2%–3% due to increased internal energy consumption for water pumps or ventilators (Greis et al. 2010). Other adaptation measures include increasing the volume of water treatment works or developing alternative sources of water. The choice of appropriate techniques to adapt to higher temperatures with water shortages can be very site specific.

Figure 2 indicates the typical range of water use, both withdrawals and consumption, for thermal and nuclear power plants in the United States. We are not aware of comparable data being available for Asia.

As power stations and related infrastructure can operate for 50 years or more, adaption measures should consider a range of projections including gradual change, more rapid changes, and possible changes in extremes over this period. For some locations, simply raising the level of structures can

Figure 2 Typical Range of Water Withdrawals and Consumption for Thermal and Nuclear Power in the United States



Note: Scale is not linear above 10 m^3 per megawatt-hour.

Source: Adapted from Figure 17 of Sauer, Amanda, P. Klop, and S. Agrawal. 2010. *Over Heating—Financial Risks from Water Constraints on Power Generation in Asia (India, Malaysia, Philippines, Thailand, Vietnam)*. World Resources Institute and HSBC Climate Change.

suffice for areas with increased danger of flooding over time. Designing decentralized generation systems reduces the need for large facilities located in areas of high risk and spreads the risk (IMechE undated), and requires less cooling power at each station, though perhaps not in aggregate. Other adaptation measures[8] (Sieber 2010, URS 2010) include

- adaptation of structures, including higher standards for new or renovated buildings, drainage improvements, rerouting of service water pipes, and construction of concrete-sided buildings[9] instead of metal-sided (as they are more resistant to wind and corrosion);
- protection of coal stockpiles through optimized shape and orientation to wind, and protection of coal stockpiles against high temperature and low water content to avoid self-ignition;
- adaption of sites including flood control (embankments, dams, dikes, reservoirs, polders, ponds, relocation of flood defense barriers, and higher channel capacity), construction of improved coastal defenses (seawalls and bulkheads), relocation to less exposed places, land restoration and afforestation to reduce floods and landslides;
- concentrating thermal investment in locations where temperatures are projected to be cooler, if the costs of additional transmission capacity and higher transmission losses are not so high as to offset gains; and
- adaptation of cooling facilities (such as water recovery from condenser and heat exchangers, reduction of evaporative losses, secondary or wastewater usage, construction of dry cooling towers).

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8 Note that these adaptation measures also apply to nuclear and other types of power plants and the measures aren't repeated in subsequent sections.

9 However, reinforced concrete structures are susceptible to corrosion by carbonation and chloride through increased CO_2 levels in the atmosphere. In the worst case IPCC projections, carbonation damage is up to 460% higher in 2100 than that of emissions at 2000 levels and chlorine-induced corrosion could rise by 15%. Reinforced concrete structures will require more robust designs to counter high CO_2 levels (Wang et al. 2010).

Gas turbine designers have various means of coping with temperature and other ambient changes. In addition to recirculating or dry cooling systems, these include inlet guide vanes, inlet air fogging, inlet air filters, techniques for washing compressor blades to manage salt and dust, and treated wastewater to reduce water taken from rivers (Neumann and Price 2009).

Box 5 summarizes the adaptation priorities identified in the rapid climate change vulnerability assessment for the planned O Mon IV thermal power plant presented earlier in Box 4.

Table 2 summarizes climate change impacts on thermal power generation and adaptation options.

2.2. Nuclear Power

Vulnerability of Nuclear Power Plants to Climate Change

Nuclear systems could account for up to 12% of electricity generation in the Asia–Pacific DMCs by 2030 (ADB 2009a). Although the 2011 Fukushima Daiichi disaster in Japan has raised questions about the future role of nuclear power globally, this has not thus far changed the policies in the People's Republic of China, India, or Republic of Korea that are driving its expansion in Asia (IEA 2011).[10]

The main climate change impacts of relevance to nuclear power are the effects of changes in water

Box 5 Adaptation to Expected Climate Change Threats to the O Mon IV Thermal Power Plant

Based on the magnitude of climate change threats and sensitivities, priorities in adaptation response for the thermal plant presented in Box 4 include the following:

- *Improving performance of the gas turbine cycle*. Focus on the gas turbine technology, with pretreatment of the intake air to reduce temperature or redesign of the topping cycle technology to accommodate a warming climate.
- *Improving performance of the cooling water cycle.* Focus on reducing the intake water temperature or increasing the performance of the cooling water system pumps and heat exchangers.
- *Improving management of the coolant discharge.* Focus on reducing the proportion of coolant feedback at the water intake structures and improving mixing of the coolant plume in the river water column.

Four main entry points for integrating adaptation planning into the project life cycle were identified:

1. the current planning phase,
2. replacement of the gas turbine (about midway through the project),
3. replacement of other major equipment (three times evenly spaced over the design project life), and
4. end of the design economic life when refurbishment and lifetime extension are being considered.

Source: International Centre for Environmental Management (ICEM). 2010. *O Mon IV Power Plant: Rapid Climate Change Threat and Vulnerability Assessment.* Prepared for Asian Development Bank. Hanoi, Viet Nam.

[10] The People's Republic of China, where 27 power reactors are under construction (40% of the global total), has been carrying out "sweeping" reviews of nuclear safety laws and regulations (Hook 2011).

Table 2 Key Climate Change Impacts and Adaptation—Thermal Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Precipitation increase or decrease	• Fuel (coal) storage • Boiler/furnace • Turbine/ generator • Cooling system	• Increase could cause reduced coal quality (and combustion efficiency) due to higher moisture content of coal • Decrease could affect availability of freshwater for cooling (all thermal systems)	• Protect fuel storage including coal stockpiles • Withdraw less water from source and consume less water internally (once-through or recirculating system) • Increase volume of water treatment works and/or develop new water sources • Redesign cooling facilities (water recovery from condenser and heat exchangers, reduction of evaporative losses, secondary or wastewater usage, construction of dry cooling towers) • Restore/afforest/reforest land
Higher air temperature	• Boiler/furnace • Turbine/ generator	• Lowered generation efficiency • Decreased IGCC system efficiency (converting coal to gas) • Lowered CCGT efficiency (gas)	• Concentrate investment in locations where temperatures are likely to be cooler • Decentralize generation
Higher wind speed	• Buildings, storage, generating plant • Air pollution control	• Damage to infrastructure • Wider pollutant dispersion	• Develop and implement higher structural standards for new or renovated buildings
Sea level rise	• Buildings, storage, generating plant	• Increased sea levels and storm surges could damage coastal infrastructure	• Develop flood control (embankments, dams, dikes, reservoirs, polders, ponds, relocated flood defense barriers, and higher channel capacity) • Construct improved coastal defenses (seawalls and bulkheads) • Construct or relocate to less exposed places • Raise level of structures • Improve drainage and reroute water pipes • Protect fuel storage
Extreme events (including flooding)	• Buildings, storage, generating plant	• Hurricanes, tornadoes, ice storms, severe lighting, etc. can destroy infrastructure and disrupt supplies and offshore activities • Possible soil erosion and damage to facilities	• As above • Develop and implement higher structural standards for new or renovated buildings • Build concrete-sided buildings instead of metal (more resistant to wind and corrosion)

Note: Integrated gasification combined cycle (IGCC) converts coal to synthetic gas and removes impurities. A combined cycle gas turbine (CCGT) power plant consists of one or more gas turbine generators with systems to recover heat in the form of steam from the turbine exhaust, the steam powering a generator to produce additional electricity.

temperature and availability, air temperature, and especially floods (European Commission 2011). Nuclear reactors require significant amounts of water to cool or condense the coolant, which transfers heat from the core to the turbines and cools the reactor core (between 2,500 and 3,200 liters per MWh). This explains why nuclear power plants are located near substantial amounts of water (i.e., near oceans, large lakes, or rivers). If climate change affects the temperature, quality, or quantity of water, then existing nuclear power plants can be adversely affected. Geographic information systems models of sea level rise and a review of existing reports and published literature suggest that numerous existing plants have already been or may be so affected (Kopytko and Perkins 2010). During the 2003 European heat wave, 17 nuclear reactors in France were forced to reduce output or shut down due to water abstraction and discharge restrictions (Acclimatise 2009). This could be a serious long-term issue for nuclear power if water resources are stressed by reduced flow and increased temperatures.

Recent studies of European nuclear power systems indicate only marginal efficiency losses as air and water temperatures increase. Others (Linnerud et al. 2011) suggest that a 1°C rise in ambient air temperature can reduce nuclear power output by about 0.5% because of reduced thermal efficiency. However, during droughts and heat waves, the loss may exceed 2% per degree Celsius because cooling systems are constrained by physical laws, environmental regulations, and reduced access to cooling water. Temperature changes affect mainly inland nuclear power. For power plants situated on the coast, which use sea water for cooling, there is hardly any temperature change impact expected, since the predicted rise of the sea water temperature is very moderate (European Commission 2010). The European Commission study suggests a more modest drop in power due to an increase in ambient air temperature (Table 3).

Climate change can affect coastal reactors in several ways (Kopytko and Perkins 2010), the effects of which can include loss of power, loss of communications, blockage of evacuation routes, equipment malfunction, and decreased structural stability following erosion caused by sea level rise.

Table 3 Temperature Effect on Nuclear Power Efficiency

Cooling Agent	Temperature Change	Power Loss
Water	+ 5°C	– 1.0%
Air	+ 1°C	– 0.1%

Source: European Commission. 2010. *Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change.* Final report. European Commission Directorate-General for Energy Report EUR 24769.

Adaptation Measures for Nuclear Power

Considering the risk of catastrophic failure and the advice provided by the International Atomic Energy Agency (IAEA) that nuclear plants be designed to last for 100 years (Kopytko 2011), it is especially important that adaptation be rigorously built into the design of nuclear power plants even for seemingly unlikely events. Consideration of both gradual sea level rise and increased storm events and associated tidal surges should be incorporated into all designs (URS 2010) based on design criteria specific to each location.

The main costs for adapting nuclear power plants to climate change, other than for extreme events, result from the reduced efficiency with higher temperatures. The expected efficiency losses are relatively small in percentage terms, but additional cooling towers cost approximately \$67–\$130 million each, and modifications to cooling water inlets at coastal locations to allow use of cooler, deeper water may cost up to \$133 million (European Commission 2011). New reactors could use dry or hybrid cooling systems with lower water requirements, but the costs of running these are likely to be very high (Kopytko 2011). Both utilities and regulators may feel that costs do not justify the small efficiency improvements. Smaller investments to develop more efficient pumps and heat exchangers could be more cost-effective.

Box 6 suggests possible corrective actions to adapt existing and new nuclear facilities to the failures experienced during the 2011 Fukushima accident. While the tsunami was triggered by a strong earthquake, storm surges may intensify in the future as a result of both stronger storms and higher sea levels. In this context, lessons from Fukushima may be of interest, particularly as the engineering design was not sufficiently robust to withstand either the earthquake or tsunami alone and recent reports suggest that the tsunami, not the earthquake, may have been the main cause of damage.[11]

Box 6 Possible Corrective Actions to Improve Nuclear Power Plant Safety: Lessons from Fukushima

MIT's initial evaluation of the 2011 Fukushima-Daichii accident presents a number of possible corrective actions for the nuclear industry for six areas of concern.

1. *Emergency Power following Beyond-Design-Basis External Events:* How can loss of power (complete station blackout) be prevented or its effects minimized?

   Possible design improvements in future plants:
   - Put in place a mix of passive and active safety systems that don't rely on external intervention.

2. *Emergency Response to Beyond-Design-Basis External Events:* How can sufficient staff be assured when many are unable to reach the plant? How can an evacuation zone be determined? How can the public be advised of the risk?

   Possible corrective actions at current and future plants:
   - Establish a rapid-response team of essential workers available for transport to a stricken plant by air.
   - Set up evacuation zone and strategies based on minimizing risk to the public from both direct damages and radiation.
   - Adopt regulatory requirements for more on-site personnel with independent and timely information and ability to influence the owner/operator behavior during the accident.
   - Ensure that radiation levels during nuclear accidents are communicated to the public using a scale that is easy to communicate and understand.

3. *Hydrogen Management:* How can hydrogen generation and accumulation be reduced?

   Possible corrective actions at current and future plants:
   - Vent pressure vessels via strong pipes connected to stack, operable when power is not available.
   - Ensure that air in the pool areas is more directly connected to the plant stacks.
   - Put in place more hydrogen recombiners (passive) and igniters (active) for small releases where hydrogen may accumulate as well as catalytic recombiners in the ventilation system and inside the containment.

continued on next page

[11] According to media reports (Bloomberg News 2011), a spokesperson for Japan's Nuclear and Industrial Safety Agency (NISA) claims that both NISA and Tokyo Electric Power believe that the quake did not cause significant damage to the plant. They blame the tsunami, which swamped backup generators, causing a loss of cooling and the meltdown of the reactors. This is not explicit, however, at NISA's website, www.nisa.meti.go.jp/english/.

Box 6. continued

- Possibly flare hydrogen for massive venting of containment gases.
- Reduce or eliminate materials that generation hydrogen when oxidized with steam.

4. *Containment:* How can the need for containment venting be eliminated or radioactivity releases minimized?

Possible corrective actions for current plants:

- When cooling is unavailable, vent directly to stack via valves with rapid backup power or manually.
- Implement automatic catalytic cooling if power is lost.

Possible design improvements in future plants:

- Implement passive containment cooling to eliminate need for venting to reduce containment pressure, when power is unavailable.
- Filter or vent containment vessels when power is unavailable.

5. *Spent Fuel Pools:* How can the spent fuel pools be better protected from external events?

Possible corrective actions for current plants:

- Retrofit pools with passive cooling.
- Review policy of unloading full core into pools.
- Move spent fuel assemblies to dry storage as quickly as possible.

Possible design improvements in future plants:

- House spent fuel pools in containment-like structures separate from reactor building.
- Build regional or national consolidated spent fuel interim storage facilities.
- Create a national spent fuel repository.

6. *Plant Siting and Site Layout:* How can failure from a common cause and unit-to-unit contagion be prevented?

Possible corrective actions for current plants:

- Improve layout diversity and separation at multi-generating unit sites.
- When expanding facilities, locate administrative buildings and parking lots between buildings.

Possible design improvements in future plants:

- Choose sites away from highly seismic areas and coasts (or stringent designs against risks).
- Carefully assess the number of units allowed at single site to reduce vulnerability, staff, and resources needed for a severe accident affecting all units.

Source: Buongiorno, J. et al. 2011. *Technical Lessons Learned from the Fukushima-Daichii Accident and Possible Corrective Actions for the Nuclear Industry: An Initial Evaluation.* Massachusetts Institute of Technology Center for Advanced Nuclear Energy Systems. Report MIT-NSP-TR-025 Rev 1.7. August.

Table 4 Key Climate Change Impacts and Adaptation—Nuclear Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
• Precipitation • Changed river flows • Higher air temperature	• Cooling system • Turbine/generator • Spent fuel storage	• Insufficient cooling water (drought, temperature, competing uses) particularly for inland plants • Decreased generation efficiency (temperature rise) for inland plants • Loss of on-site power, leading to severe interruptions to safety and operations for inland and coastal plants	• Formulate long-term strategies to respond to climate-related disruptions. • Install additional cooling towers and modify cooling water inlets at coastal locations. • Use dry or hybrid cooling systems with lower water requirements. • Develop more efficient pumps and heat exchangers.
• Sea level rise • Floods • Extreme or multiple events	• Cooling system • Turbine/generator • Spent fuel storage • Emission control system	• Flooding from heavy rainfall, storm surges, or sea level rise • Catastrophic failure with radioactive leaks and widespread evacuations of population, particularly for coastal locations	• Require more stringent safety investments. • Incorporate gradual sea level rise, increased storm events, and associated tidal surges into design criteria. • Formulate long-term strategies to respond to climate-related disruptions.

Note: In addition, many of the issues regarding vulnerability of thermal power plants are applicable to nuclear.

Table 4 summarizes key impacts of climate change on nuclear power systems as well as possible adaptation options.

2.3. Renewable Energy—General

Vulnerability of Renewable Energy to Climate Change

Renewable energy, including hydropower, is projected to provide nearly 17% of Asia–Pacific DMC electricity supply in 2030 (ADB 2009a), more than gas (15%), nuclear (12%), or oil (under 2%). Although output from some renewable energy sources may be relatively unaffected by weather or climate change (such as geothermal and tidal sources of energy), several others are linked closely to short-term seasonal variations and climate change (bioenergy, hydropower from reservoirs, and small hydropower systems). Energy from sources such as wind, sea wave, photovoltaic, and solar concentrating power systems (solar photovoltaic or thermal) is directly related to fluctuating weather conditions (Bremen 2010)—for example, wind energy to wind speeds and solar energy to incoming solar radiation. This renewable energy variability, whether or not predictable, can have implications for grid stability as discussed further in Section 3.[12]

[12] Power systems must maintain accurate frequency (50 or 60 Hz) and voltage with a continuous balance between supply and demand, transferring electricity between generation and demand through transmission and distribution grids that have limited capacity. Even if renewable energy output is highly predictable (e.g., tidal), generation may be poorly correlated with times of high demand. Higher levels of investment in more intermittent forms of renewable energy (e.g., solar, wind) can result in problems with grid stability. A challenge for most renewable energy is that renewable resources are location specific and renewably generated electricity may need to be transported over considerable distances (Gowrisankaran et al. 2011, IPCC 2011).

In general, renewable energy system output will be vulnerable to any climate changes that increase the variability of energy input or decrease its predictability. The extent to which different aspects of intermittency balance out depends on how a particular renewable energy source affects choices of generator scheduling, operating reserves, and backup capacity. These in turn crucially depend on three factors: (i) the variability of the source including the extent to which the variability correlates with demand, (ii) the extent to which output from the source can be accurately forecast, and (iii) the costs of building backup generation. These general issues of intermittency for renewable power are well understood (Gowrisankaran et al. 2011).

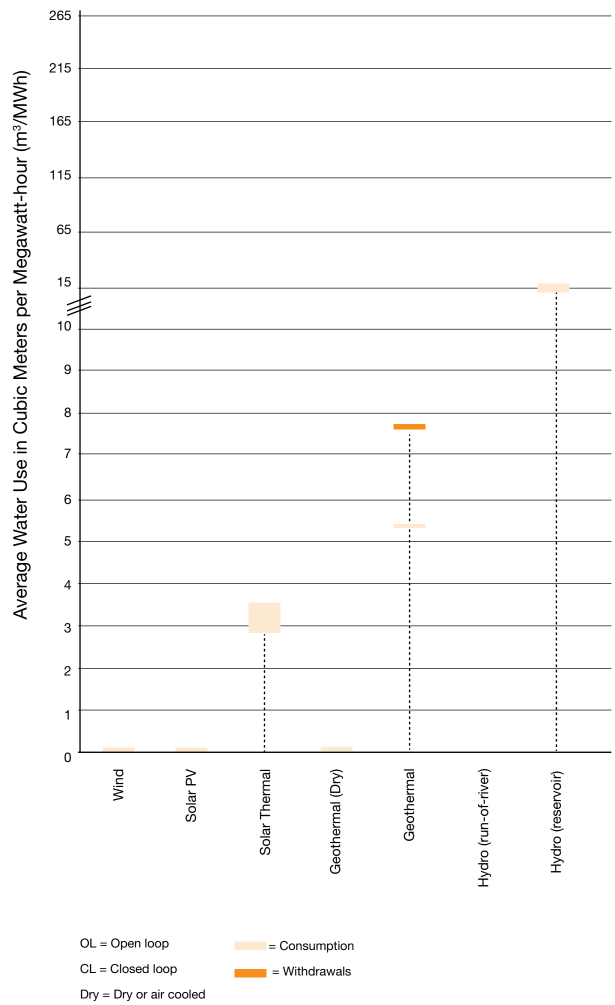
Figure 3 indicates typical ranges of water withdrawals and use for power generation from renewable sources in the United States. The range for biomass and waste-to-energy systems is the same as coal (Figure 3). Wind, solar photovoltaic, and dry geothermal systems consume relatively small volumes of water.

Adaptation Measures for Renewable Energy in General

Adaptation measures for specific renewable energy technologies are discussed in greater detail in the following sections. However, it should be noted that any climate change that increases variability or lowers predictability is likely to require higher levels of investment to safely integrate renewable energy into the grid or improve grid load capacity. Higher levels of investment in more intermittent forms of renewable energy (solar, wind) are also likely to require network expansion and/or protection (IPCC 2012).

A complementary approach to adaptation of renewable energy systems under increased climate variability is storage of electrical energy to allow a greater percentage of renewable energy into the grid. By storing energy (in batteries, flywheels, compressed

Figure 3 Typical Range of Water Withdrawals and Consumption for Power from Renewable Sources in the United States



PV = photovoltaic

Source: Adapted from Figure 17 of Sauer, Amanda, P. Klop, and S. Agrawal. 2010. *Over Heating—Financial Risks from Water Constraints on Power Generation in Asia (India, Malaysia, Philippines, Thailand, Vietnam)*. World Resources Institute and HSBC Climate Change.

air, water reservoirs, pumped hydro, etc.) when renewable output is high and the demand low, and generating when renewable energy output is low and the demand high, grid stability can be improved and baseload generation units can operate more efficiently. Storage can also reduce transmission congestion and may reduce or delay the need for transmission upgrades (IPCC 2012), but cost-effective applications are site specific.

Various renewable energy sources and technologies are considered in turn below.

2.4. Hydropower

Vulnerability of Hydropower to Climate Change

In general, climate change and the modification of rainfall and temperature patterns can affect hydropower output in four major ways: (i) surface water evaporation, (ii) reduced runoff due to drought, (iii) increased runoff due to flooding, and (iv) siltation (Mukheibir 2007). Higher precipitation could increase seasonal river flows, but higher evaporation could reduce water storage in the reservoir. Increased variability in weather (intensity of peak flows, changes in seasonal patterns) could increase uncertainty in river flows and the capacity of reservoir storage (e.g., days of stored water supply), disrupting expected supply patterns (Harrison et al. 1998). Run-of-river hydropower systems, which by definition lack water storage, are significantly affected by daily, dry-season, wet-season, and annual changes in precipitation.

Recent climate models suggest a general decrease in precipitation and river runoff for the mid-latitude subtropical areas where hydropower is often a primary source of electricity (Water News 2010). In general, a 1% change in precipitation is likely to result in at least a 1% change in power generation (Neumann and Price 2009)[13] although changes in power generation are harder to predict for run-of-river systems.

Other potential impacts of climate change on hydropower can be wide-ranging and severe, as illustrated by a recent study of the Mekong River basin (Box 7).

Increased glacial melting and associated glacier flooding, landslides, and avalanches could have significant impacts on hydropower in parts of Nepal (Box 8), Bhutan, People's Republic of China, Pakistan, and elsewhere (Horstmann 2004, ICIMOD 2011, Khadka 2011).

ADB recently sought advice on whether climate change analysis could improve the design and planned operations of hydropower plants in the Kyrgyz Republic and Tajikistan, where the evolution of temperature and precipitation regimes will affect future glacier melt and runoff. Twenty-two regional and global climate models were assessed (Roy 2009) showing a narrow range of projected temperature changes by 2050 and 2080 but a large range for precipitation changes. On average, the models suggest a slight increase in annual precipitation, with a significant reduction of precipitation in summer and an increase in winter. Glacier shrinking may increase in the coming decades and the projected change in precipitation is uncertain, but the extent of agreement regarding future temperature suggests that the projected runoff conditions are likely. The analysis also suggests that likely changes should not affect the design of new power stations or the operation of existing ones through 2050, but over the longer term the availability of water resources may be threatened by the limited amount of fossil water stocked in the glaciers.

[13] Studies from the Colorado River in the US suggest that relatively modest changes (a temperature increase of 2°C and a 10% decline in precipitation) might reduce river runoff by up to 40%, which could have a substantial impact on generation (Urban and Mitchell 2011).

Box 7 Climate Change Impact of Hydropower on the Mekong River

More than 11 hydropower dams are currently being studied by private sector developers for the mainstream of the Mekong River. The most important direct climate change effects on the mainstream projects would be through

- the increase in annual runoff (CSIRO estimate by 21%), bringing with it increases in sediment load;
- an increase in flow in the range of 9% to 22%, taking into account the Upper Mekong Basin and Lower Mekong Basin mainstream and tributary dams; and
- an increase in the incidence, depth, and duration of extreme flood waters.

Lower Mekong Basin mainstream dams could be subject to seasonal and extreme event peaks in flow well beyond their normal operating design standards. The complex interlinkages between climate changes, the mainstream dams, and other trends in the basin would result in significant indirect and synergistic effects such as

- reduced food security (aggravated by mainstream dams),
- changes to water quality (as above),
- loss of biodiversity (with increased natural system instability),
- constraints to poverty reduction (due to above factors), and
- increased potential tributary and mainstream hydropower production (due to increased annual runoff and flow throughout all catchments of the basin).

CSIRO = Commonwealth Scientific and Industrial Research Organization, Australia

Source: International Centre for Environmental Management (ICEM). 2010. *O Mon IV Power Plant: Rapid Climate Change Threat and Vulnerability Assessment*. Prepared for Asian Development Bank. Ha Noi, Viet Nam.

Box 8 Glacier Melting, Glacial Lake Outburst Floods, and Hydropower in Nepal

Glaciers are considered to be sensitive indicators of increased air temperature. While the global average temperature has risen by about 0.75 °C in the last 100 years (IPCC 2001), the warming in the Nepal Himalayas increased by 0.15°C to 0.60°C every 10 years during the last 3 decades (Shrestha et al. 1999).

One of the most visible impacts in the Himalayan region is the faster rate of retreat of its glaciers compared with those of other mountain ranges. This accelerated melting of glaciers causes increased river flows and flooding in the short term and a decrease in glacial runoff and river flows in the long term, affecting the water supply for hydropower plants (Pathak 2010). Extreme events such as glacial lake outburst floods (GLOFs) can cause catastrophic damage to hydropower infrastructure. Nepal has experienced 24 GLOFs in recent years including that of the Dig Tsho in 1985, which destroyed the nearly completed Namche hydro project (Thomas and Rai 2006).

Continuing glacial melting and the impossibility of reliably predicting a specific occurrence of GLOF based on existing knowledge (ICIMOD 2011) highlights the vulnerability of hydropower systems in glacial mountain regions.
Khimti 1 is a 60-megawatt hydro installation 100 km east of Kathmandu that generates 350 gigawatt-hours per year. Winter mean temperature is projected to increase 0.8°C–3.4°C by the 2030s, rising to 2.0°C –5.0°C by the 2060s. Summer increases are projected at 0.5°C–2.0°C by the 2030s, and 1.1°C–3.5°C by the 2060s. For precipitation, the mean projection is a 7% decrease in winter by the 2030s (12% by the 2060s), while for summer, rainfall will increase by 2% by the 2030s (8% by the 2060s). However, the rainfall estimates are uncertain and baseline data do not allow an informed estimate of the increased risk of flooding.

continued on next page

Box 8. continued

Rainfall and temperature changes pose the following risks (IFC 2011):

- significantly lower dry season generation (high confidence in rainfall/output link but low confidence in rainfall model);
- no change to wet season generation or revenue (as Khimti operates at full capacity);
- extreme flooding with sedimentation and damage to intake structures (low confidence, poor baseline data);
- landslides blocking and flooding the river upstream and/or blocking road access, affecting generation and revenue (qualitative assessment only);
- decreased yields by subsistence farmers (but low confidence in models and minimal impact on Khimti output);
- increased risk of GLOFs due to widespread and accelerating loss of glacier mass and deterioration of moraine dams (but low confidence in estimating financial impact due to poor baseline data); and
- pressure to increase minimum flow to increase downstream irrigation (with high confidence in adverse effects on output and revenue).

Adaptation Measures for Hydropower

Considering that hydropower is a long-term investment with typical lifetimes of 50 to 100 years, assessing changes that might affect output and operation is important. The Tajikistan/Kyrgyz study (Roy 2009) demonstrates the value of carrying out an initial analysis based on recent climate change models covering the location of proposed hydropower development to estimate the likely range of projected variations in climate, which can improve confidence in planning and reduce costs that may be unnecessary. Although results suggest that design changes may not be needed, similar studies elsewhere might identify cost-effective modifications or conclude that more detailed studies are required to determine the costs and benefits of adapting designs to deal with specific risks identified for the site.

Hydropower plants are normally robust, an increase in the strength or frequency of storms or cyclones only marginally increasing the risk of destruction. Nonetheless there are various measures to better adapt hydropower systems to climate change (Michaelowa et al. 2010, WWF undated):

- increase dam height and/or build small dams upstream (where flow is expected to increase);
- design more robust dams and infrastructure for heavier flooding and extreme events;
- construct or augment water storage reservoirs;
- modify spillway capacities and install controllable spillway gates to flush silted reservoirs;
- modify the number and type of turbines that are better suited for expected water flow rates and more resilient to performance reductions and turbine lifetime due to higher suspended sediment loads;
- modify canals or tunnels to better handle changes in water flows;
- allow for increased flows from glacier melting if they are likely to persist over the technical lifetime of the system’s increased capacity;
- develop improved hydrological forecasting techniques and adaptive management operating rules;
- develop basin-wide management strategies that take into account the full range of downstream environmental and human water uses; and
- restore and better manage upstream land including afforestation to reduce floods, erosion, silting, and mudslides.

Structural design measures are suited to adaptation for both existing infrastructure and future developments, and can have secondary environmental or social

Box 9 Improving Efficiency of Existing Hydropower Generation through Climate Modeling in Fiji and Papua New Guinea

The electricity utilities of Fiji and Papua New Guinea have operated hydropower systems for more than 30 years. There are detailed data on rainfall and weather patterns in the catchment areas for this period as well as good historical records of reservoir water levels and water releases through the power tunnel and turbines. However, the data have not been analyzed, the duration and intensity of rainfall have not been measured, and operational decisions are made on an ad hoc basis, resulting in inefficient use of water resources for power generation.

The peak demand on Fiji's main island of Viti Levu is 135 MW. Hydropower can provide about 90 MW when operating at full capacity, of which 80 MW is produced by the Monasavu hydro system, the difference provided mostly by petroleum generation with small amounts of biomass and wind. During periods of drought, hydropower generation falls well below full capacity. 2009/10 was an El Niño year when low rainfall necessitated considerable generation from diesel and fuel oil, at a fuel cost of $71 million, double the planned fuel expenditure.

A 3-year study has been proposed to analyze existing data, install automated rain gauges in the vicinity of existing manual recording stations to verify and calibrate historical data, and develop a weather/climate model for forecasting rainfall events and reservoir water level dynamics. The objective is development of easy-to-use models for reservoir operators to better regulate outflow and power generation, decreasing dependency on fossil fuels, especially during periods with low water levels.

In the short term, fuel use for power generation is expected to drop by at least 15% in both Fiji and Papua New Guinea, separate from savings through other options for improving catchment, dam, and power generation facilities to further improve efficiency of water use. For the longer term, the model could incorporate climate projections recently completed by the Australian Commonwealth and Industrial Research Organisation to assist the utilities to further improve reservoir management at existing hydro facilities and improve designs for proposed new systems. For both countries, extreme rainfall days are projected to occur more frequently in the future. Projections suggest that Fiji will experience increased wet season rainfall and decreased dry season rainfall. Projections for Papua New Guinea suggest both annual and seasonal increases in rainfall but there are some inconsistencies in the models. For both countries, incorporation of these results into hydro planning could have significant impacts on the efficiency of use of hydro resources.

Sources: Australian Government. 2011. *Climate Change in the Pacific: Scientific Assessment and New Research*. Volume 2: Country Reports (Fiji and Papua New Guinea); Fiji Electricity Authority (FEA). 2011. *FEA Annual Report for 2010*; and Liebregts, W. 2011. Personal communications with director of Eco-Consult Pacific Co. Ltd. August 2011.

effects that require careful analysis. Non-engineering measures can be integrated into existing or future developments and typically require the involvement of numerous stakeholders within the river basin. For existing hydropower infrastructure, localized (regional) climate modeling might suggest operational changes to optimize reservoir management and improve energy output by adapting to changes in rainfall or river flow patterns (Box 9).

Table 5 summarizes key climate change impacts and adaptation options for hydropower.

Table 5 Key Climate Change Impacts and Adaptation—Hydropower

Climate Variable	Physical Components	Key Impacts	Adaptation Options
• Precipitation • Temperature • Extreme events	• Dam and other structures (intake, penstock) • Power station (turbines and generators)	• Indicated below for specific climate changes	• Develop improved hydrological forecasting techniques and adaptive management operating rules • Develop basin-wide management strategies that take into account the full range of downstream environmental and human water uses • Restore and better manage upstream land including afforestation to reduce floods, erosion, silting, and mudslides • Analysis to estimate likely range of projected climate variations over hydro lifetime • Identify cost-effective designs (new plants) and modifications (existing plants) to deal with specific risks identified for the site
• Precipitation (including drought)	• Dam and other structures • Power station	• Changing annual or seasonal patterns can affect river flows and water levels behind dams, either reducing or increasing power output • Siltation can reduce reservoir storage capacity • Increased uncertainty in water flows can affect power output and generation costs	• Increase dam height and/or build small dams upstream (if flow is expected to increase) • Construct or augment water storage reservoirs • Modify spillway capacities and install controllable spillway gates to flush silted reservoirs • Modify number and type of turbines more suited to expected water flow rates • Modify canals or tunnels to handle expected changes in water flows • Optimize reservoir management and improve energy output by adapting to changes in rainfall or river flow patterns
• Extreme events (glacier melting, floods)	• Dam and other structures • Power station	• Floods and glacial lake outburst floods can damage or destroy infrastructure	• Design more robust dams and infrastructure for heavier flooding and extreme events • Design for increased flows from glacier melting
• Higher air temperature, wind speeds, and humidity	• Dam and other structures	• Can increase surface evaporation, reducing water storage and power output.	• Construct or augment water storage reservoirs

2.5. Wind Power

Vulnerability of Wind Power to Climate Change

The energy content of wind is proportional to the wind speed to the power of 3—a 15% increase in wind speed results in 52% more energy. In practice, however, wind turbine output follows a sigmoid (S-shaped) curve with energy production flattening or decreasing at high wind speeds. Nonetheless, output is highly dependent on wind speeds, with a small change having a substantial impact on electricity generation, revenue, and financial viability. Other variables that affect wind turbine output are atmospheric pressure, ambient temperature, humidity, and air density (Nikolova 2010), although the latter effect is minimal: a 1°C rise in temperature lowers air density and power by approximately 0.33% (Harrison et al. 2008).[14]

Cold temperatures with precipitation can reduce blade aerodynamic efficiency and cause damage, particularly if thick ice forms. Although engineering designs incorporate allowances for increased loads, extreme events with ice buildup or very strong and variable gusting winds pose a serious risk to foundations, towers, and other components (Laakso et al. 2006). Based on models and observations, there is some evidence for a weakening of tropical surface wind extremes in response to atmospheric warming (Gastineau 2011).

Even if average annual wind speeds remain unaltered, a change in the diurnal wind pattern can affect daily wind power production, significantly improving—or reducing—the match between wind energy input to the grid and daily load demands (Wilbanks et al. 2008). Abnormally weak seasonal winds can also significantly reduce annual energy production (Baker et al. 1990). Changes in the frequency distribution, average speed, and timing of winds affect turbine performance and ultimately energy output (Harrison et al. 2008). Hence, any increased variability in wind characteristics creates challenges for the accurate prediction of wind power output and the financial viability of wind energy systems. Wind speeds and changes in the pathways of storms and hurricanes are particularly difficult to predict with current climate models.

There can be four types of impacts on offshore wind farms from climate-induced changes such as higher sea level, sea ice from melting ice sheets, and wind and sea wave loads (Pryor and Barthelmie 2010):

- Drifting sea ice can damage wind turbine foundations offshore.
- Sea level rise could damage turbine foundations in low-lying coastal areas.
- Corrosion of structures is expected to decrease as freshwater ocean loading increases.
- Combined action of wind and wave loads may increase, damaging foundations, so offshore turbines would need to withstand greater forces.

Adaptation Measures for Wind Power

Wind turbines are often designed to deal with a wide range of conditions, but where wind speeds are expected to increase, designs can be adapted to capture more energy and produce more electricity. Adaptation options include the following (Ebinger and Vergara 2011, Michaelowa et al. 2010, Pryor and Barthelmie 2010):

- Construct turbines that can operate at, and physically withstand, higher wind speeds and higher wind gusts.

[14] Pryor and Barthelmie (2010) state that a 5°C increase in air temperature, from 5°C to 10°C, leads to a decrease in air density of 1%–2%, with a commensurate decline in energy density.

- Use taller towers to capture the stronger winds at higher altitudes.
- Consider the development and commercialization of vertical axis wind turbines, which are less sensitive to rapid changes in wind direction and could potentially yield an order of magnitude increase in wind farm energy output per unit of land area, as vertical axis systems can be placed close together without significant turbine wake effects (Dabiri 2011).
- Choose sites that take into account expected changes in wind speeds during the lifetime of the turbines, as well as sea level rise and changes in river flooding.
- Consider the effects of extreme low and high temperatures in turbine selection and operation as these can alter physical properties of materials (e.g., rubber seals may become brittle at low temperatures; hydraulic systems and lubricant needs may change).
- Design offshore turbine designs to withstand expected increases in wind–sea wave forces.
- Ensure the presence of rapid emergency repair teams to repair damaged turbines quickly.

Box 10 describes issues faced by the People's Republic of China in integrating increased amounts of wind energy into the grid,[15] as well as several technical approaches to improve grid stability. Protective systems of this nature are not required specifically because of climate change but may be even more necessary if climate change results in more variable winds.

Table 6 summarizes the key climate change impacts on wind energy systems and adaptation options.

Box 10 Absorbing Wind Energy into the Grid and Maintaining Grid Stability

The People's Republic of China (PRC) is the world leader in installed wind energy capacity, with nearly 42 gigawatts at the end of 2010. However only 66% was grid-connected, partly due to issues with grid stability, specifically "low-voltage ride through" (LVRT), the capability to cope with the stresses of fast rises and drops in voltage, allowing the grid to maintain a consistent flow of electricity. The State Electricity Regulatory Commission (SERC) confirms that many wind farms already connected to the grid have no or little LVRT capability, causing power supply and stability problems (Ma and Fu 2011).

The highest energy demand is in the PRC's central and southeastern regions, but the country's most abundant wind resources are located in the north. There are limitations to the grids' capacity to transmit power to distant regions, as well as inadequate capacity of many northern grids to absorb the region's rapidly growing wind-generated electricity. Addressing the former requires investment in new grid capacity. To address the latter, SERC has recently recommended that all wind farms use LVRT systems to maintain operations at times of large voltage dips, and also install static var compensation (SVC) *systems, which quickly adjust wind system output to the power system's voltage, thus improving power factor, overall safety, and stability of the grid (EcoSeed 2011). Regulations are being developed to require these control systems.

* var = volt-ampere reactive. An SVC, termed static because it has no moving parts other than circuit breakers, is an impedance matching device designed to bring the system closer to unity power factor.

[15] This is potentially an especially important issue for very small power grids such as those of Pacific DMCs where governments have very ambitious goals for renewable energy fed to the grids.

Table 6 Key Climate Change Impacts and Adaptation—Wind Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
General	• All	• Those listed below	• Develop meteorology-based weather/climate forecasting.
Wind speed	• Rotor blades/shaft • Tower/foundation • Generator	• Changes in wind speed can reduce generation (turbines cannot operate in very high or very low winds). • Within operational wind speeds, output is greatly affected by wind speed. • Changes in wind patterns and duration affect output (e.g., ability to forecast output).	• Design turbines able to operate with and withstand higher wind speeds, gusts, and direction changes • Install taller towers to capture stronger winds at higher altitudes. • Choose sites that take into account expected wind speed changes during the lifetime of the turbines. • Consider developing and commercializing vertical axis wind turbines (more output per m^2 of land area; can operate in wider range of wind speeds).
Air temperature	• Rotor blades/shaft • Generator	• Changes in extreme cold periods can affect output (e.g., through turbine blade icing).	• Consider effects of extreme temperatures on turbine and blade selection and operation.
Storm surges	• Tower/foundation	• Damage to offshore wind farms	• Stronger structures
Extreme events	• Rotor blades/shaft • Tower/foundation	• Damage infrastructure • Difficult access to offshore locations (e.g., for maintenance)	• Design offshore turbines to withstand expected increases in wind–sea wave forces. • Insure against impact of storms on long-term power yields and damage. • Ensure presence of rapid emergency repair teams.

2.6. Solar Photovoltaics

Vulnerability of Solar Photovoltaic Systems to Climate Change

Solar photovoltaic panels have an operating lifetime of 20 or more years and photovoltaic systems are vulnerable to hail, wind, and extreme temperatures (Patt et al. 2010). Solar cell output is usually rated at 25°C with output typically decreasing by about 0.25% (amorphous cells) to 0.5% (most crystalline cells) for each temperature rise of 1°C. Cell temperatures for roof-mounted arrays in warm climates can easily reach 50°C–75°C. At 50°C, output can be 12% below rated output (Solar Facts, undated).[16]

Studies consistently show that the inverter, which converts direct current power output into alternating

[16] The energy output of 15 monocrystalline home solar systems in Sydney, Australia, where array temperatures can reach 30°C–40°C above ambient, decreased by 6% when ambient temperature rose from 25°C to 36°C (Watt et al. 2004). However, some modules are reported to exhibit outstanding performance even under extremely high ambient temperatures (Protogeropoulos et al. 2010).

current (DC to AC), is the most unreliable component of a photovoltaic system, accounting for up to 69% of unscheduled maintenance costs (Patt et al. 2010). However, they are not usually directly exposed to the weather and are not especially vulnerable to climate change.

During cloud cover, solar photovoltaic panel output can decrease by 40%–80% within a few seconds, increasing just as dramatically when the sky clears (Kleissl 2010). For large arrays, this rapid fluctuation can cause localized voltage and power quality concerns (Mills et al. 2009) because shading of one panel affects the entire array connected to a single inverter.

Higher wind speeds can increase dust particle deposits, which decrease solar photovoltaic cell output (Goossens and Van Kerschaever 1999), but higher winds can also cool the modules, increasing efficiency and output. In arid regions, higher wind speeds can also result in panel damage from increased abrasion.

Adaptation Measures for Solar Photovoltaic Systems

The main climate impacts on photovoltaic systems are likely to be due to temperature increases, increased cloud cover, and extreme events. Adaptation measures (Michaelowa et al. 2010, Patt et al. 2010) include the following:

- Assure structures are strong enough to withstand higher winds (although roof-mounted structures cannot be more robust than the building on which they are located).
- Use designs that improve passive airflow beneath photovoltaic mounting structures, reducing panel temperature and increasing power output.
- For locations where temperature increases or significant heat waves are expected, choose modules with more heat-resistant photovoltaic cells and module materials designed to withstand short peaks of very high temperature.
- Consider distributed systems (rather than feeding power into a single part of the grid), which can improve grid stability (although mobile repair teams may be needed to repair damage from extreme events).
- Where possible, site solar photovoltaic systems where expected changes in cloud cover are relatively low, although this is difficult to accurately predict.
- Where snowfalls are heavy or likely to increase, assure free space so that snow can slide off the panel.
- Where solar energy is likely to become more diffuse with changes in cloud cover, rough-surfaced photovoltaic modules are more efficient and output can be improved under overcast conditions by selecting an appropriate tilt angle.
- Where clouds are likely to pass over modules more quickly, consider micro-inverters for each panel (in place of small numbers of large centralized inverters) to improve stability and increase power output.[17]

Table 7 summarizes the key climate change impacts on solar photovoltaic systems and adaptation options.

2.7. Concentrating Solar Power and Solar Tracking Systems

Vulnerability of Concentrating Solar Power and Solar Tracking to Climate Change

Concentrating solar power (CSP) systems, whether photovoltaic or thermal, use mirrors or lenses to concentrate a large area of sunlight onto a much smaller area, thus concentrating the solar energy. CSP systems require a large amount of water for cooling purposes (between about 3,200 and 3,500 liters per MWh), typically more per unit of electricity generated than traditional fossil fuel facilities with wet cooling

[17] There have been claims of 20% improvements in performance/price ratio with micro-inverters (The Engineer 2011) and 5%–25% improvements in efficiency (Patel 2009), but recent manufacturer's tests (Williamson 2011) suggest that micro-inverters outperform the National Renewable Energy Laboratory's (NREL) "PVWatts" calculator predictions by 8% on average, with most sites improving by 10% or more.

Table 7 Key Climate Change Impacts and Adaptation—Solar Photovoltaic Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
General	• All	• Those listed below	• Develop meteorology-based weather/ climate forecasting.
Temperature increases	• Solar PV array • Control system, inverters, cables	• Lowers cell efficiency and energy output • Lowers capacity of underground conductors if high ambient temperature • Increases soil temperature	• Improve airflow beneath mounting structure to reduce heat gain and increase outputs. • Specify heat-resistant PV cells and module components designed to withstand short peaks of very high temperature.
Precipitation increases	• Solar PV array • Control system, inverters, cables • Mounting structure	• Can wash away dust (short term) but reduces panel efficiency (less solar radiation) • Snow accumulation on panel reduces efficiency	• Select appropriate tilt panel angle to clean dust. • Select module surface conducive to self-cleaning. • Choose locations with lower probability of dust, grit, snow if practical.
Wind speed; Turbidity	• Solar PV array • Control system, inverters, cables • Mounting structure	• Increased efficiency and output with cooling effect of wind • Scouring of panel and lower output if air is gritty/dusty	• Design structures to withstand higher winds. • Assure free space (panels & mounting) so snow can slide off panel. • In dry areas, consider panel rinsing system to remove dust and grit.
Cloud cover	• Solar PV array • Control system, inverters, cables • Mounting structure	• Increase lowers efficiency/output • Rapid fluctuations in cloud cover can destabilize grid	• Consider distributed systems (rather than feeding power into single part of the grid) to ameliorate cloud impact. • Site PV systems where expected changes in cloud cover are relatively low. • Consider micro-inverters for each panel (in place of small numbers of large centralized inverters) to improve stability and increase power output.
Extreme events (flood, typhoons, drought)	• Solar PV array • Control system, inverters, cables • Mounting structure	• Can damage systems (e.g., lightning strikes)	• Specify stronger mounting structure • Specify cabling and components that can deal with high moisture content and flooding.

PV = photovoltaic

(Carter and Campbell 2009). As with photovoltaic systems, cloudiness reduces energy output and strong winds could damage the installations (Patt et al. 2010). CSP and other solar tracking technologies use a system of motors to orient the lenses, panels, reflectors, etc. toward the sun. For solar photovoltaics, tracking can increase output by 30%–45% compared with a fixed array, but the systems and supporting infrastructure are susceptible to damage from high or gusting winds. They are unsuitable for locations where cyclones or hurricanes are prevalent or may increase in frequency or intensity with climate change.

Adaptation Measures for Concentrating Solar Power and Solar Tracking

Where temperatures are likely to increase, it may be of interest to consider forced air and liquid coolant systems (Patt et al. 2010). Where water shortages are expected, air cooling is possible, although more expensive than water cooling. Box 11 describes a 15-MW project under construction in Spain, which is expected to be the world's first commercial-scale CSP plant that consumes almost no water.

CSP and other solar tracking systems are generally only considered for relatively large solar installations. As with standard photovoltaic systems, adaptation of CSP technologies to deal with stronger winds requires engineering designs with robust structures. For any tracking solar system, the motors and their mounting must be especially robust wherever stronger winds, and particularly more intense storms and gusts, are expected. Key climate change impacts and adaption options are summarized in Table 8.

Box 11 Waterless Commercial-Scale Concentrating Solar Power Plant

Concentrating solar power systems normally require a great deal of water for cooling, making them unsuitable for water-deficient locations. The world's first commercial-scale concentrating solar power plant—two 15-MW units costing about $170 million—that consumes almost no water is under construction in Murcia in southern Spain. Flat mirrors reflect sunlight onto absorber tubes where water is evaporated to saturated steam at temperatures up to 285°C and 75 bar (unit of pressure) and then fed directly into a steam turbine. The air-cooled condensing system is less efficient and more expensive than water cooling, but the developers hope that simple design, minimal water needs (including cleaning), and low land requirements will make it economically viable.

Source: Kernan, A. 2011. *The world's first waterless commercial-scale concentrated solar power plant.* Leonardo Energy.

Table 8 Key Climate Change Impacts and Adaptation—Concentrating and Tracking Solar Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
General	• All	• Those listed below	• Develop meteorology-based weather/climate forecasting.
Wind; extreme events (cyclone)	• Mirrors/ concentrators • Tracking system/ motors • Support structure	• Highly vulnerable to damage to infrastructure from high or fluctuating winds	• Specify robust structures that can handle high and fluctuating winds. • Avoid tracking systems where cyclones are expected to increase in strength.
Precipitation decrease	• Boiler/turbine • Cooling system	• Water is required for steam so reduced output with less water • Possible damage from overheating with insufficient cooling water	• Where water shortages are expected, consider air cooling.
Temperature increase	• Cooling system	• Increased water required for cooling with temperature rise	• Consider air cooling.
Cloud cover increase	• Mirrors/ concentrators	• Reduced efficiency with increased cloud cover	• Choose locations where cloud cover not expected to increase.

Note: Vulnerabilities and adaptation options listed under photovoltaic energy also apply to concentrating and tracking solar systems.

2.8. Bioenergy: Biomass Energy and Biofuels

Vulnerability of Biomass Energy and Biofuels to Climate Change

Thermal power plants that burn biomass directly or use biofuels face the same general threats as other thermal generation, as discussed in Section 2.1. There are also vulnerabilities specific to feedstock, and these are covered in this section. A challenge for biomass-fed electric power plants is the effect of severe weather events such as droughts, floods, strong winds, and forest fires (due to extended drought) in the cultivation of feedstock. Power plants could be forced to run at a lower utilization rate if feedstocks are not available, but alternatively there could be a higher biomass harvest due to an increased growing season and more rainfall (Urban and Mitchell 2011). Rainfall quantity (amount and timing) can also affect the moisture content of the soil (affecting yields) or feedstock quality (resulting in low-energy feedstock inputs at the generating plant). Wind velocities can affect the dispersion characteristics of pollutant emissions. As CO_2 concentrations increase, some quick-growing varieties (which are often less dense) can out-compete more dense vegetation species, which over time can reduce energy content per unit area of land. Also, plants with different photosynthetic mechanisms (e.g., C4 and C3) respond differently to CO_2, so feedstock impacts will vary depending on the biomass source used.

Adaptation Measures for Biomass Energy and Biofuels

Adaptation measures for bioenergy systems are similar to those of other high-intensity agriculture. The Food and Agriculture Organization (FAO) has carried out numerous studies on improving climate change resilience in agriculture, some results of which are summarized in Box 12. These are equally applicable to bioenergy and mixed energy/food production systems.

Biomass availability for energy during climate change can be increased if the crops selected are robust, with high biological heat tolerance and water stress tolerance. Expansion of irrigation systems or improvement of the efficiency of irrigation can counteract drought impacts if sufficient water is available from sources outside drought-hit areas. This might require unconventional sources such as desalinated seawater or fossil water resources (Michaelowa et al. 2010). Flood protection can be improved by building dikes and improving drainage. The use of salt-tolerant plants (halophytes)—including varieties of sugarcane, millet, and corn that grow in brackish water on saline land—can provide biomass for energy without competing with conventional agriculture (Abideen et al. 2011).

If they can't be constructed in less flood- and storm-prone areas, the robustness of biomass power plants should be increased. Behavioral adaptation measures include early warning systems for seasonal rainfall and temperature anomalies, support for emergency harvesting for an imminent extreme event, and provision of crop insurance systems.

A summary of impacts of climate change on bioenergy and adaptation options is provided in Table 9.

2.9. Geothermal Power

Vulnerability of Geothermal Energy to Climate Change

There is generally only a limited impact of climate change on geothermal energy technologies (Ebinger and Vergara 2011), the main concerns being damage to the power plant and piping infrastructure and the impacts on generation efficiency and cooling water requirements (Wilbanks et al. 2008). Water use is reportedly only 19 liters per MWh (Kagel et al. 2007), which is comparable to wind and solar photovoltaic systems (Table 7), and air-cooled plants require no freshwater.

Geothermal generation uses steam turbines, so a reduction in the difference between ambient and combustion temperature lowers overall operating efficiency (Contreras-Lisperguer and de Cuba 2008). Geothermal energy is also vulnerable to ambient temperature rise, which may also affect air and underground temperature differential and energy output (McColl and Palin 2009).

Box 12 Measures to Improve Climate Resilience of Bioenergy Systems

The Food and Agriculture Organization (FAO) advocates merging adaptation, mitigation, and even prevention to produce an overall strategy of "resilient adaptation" for agricultural systems. The conclusions are equally valid for biomass and biofuel energy, with many actions worth undertaking even in the absence of climate change, much of which is likely to be incremental and slow in onset but cumulative. Efficiency, resilience, adaptive capacity, and mitigation potential of agricultural production systems can be enhanced through improving their components, as highlighted below:

- *Water harvesting and use.* Improved water harvesting and retention (pools, dams, pits, retaining ridges, etc.) and water-use efficiency (irrigation) are fundamental for increasing production and addressing increasing irregularity of rainfall patterns.
- *Pest and disease control.* Climate change appears to be altering the distribution, incidence, and intensity of animal and plant pests and diseases as well as invasive and alien species. The recent emergence of multi-virulent, aggressive strains of wheat yellow rust adapted to high temperatures is indicative of risks associated with pathogen adaptation to climate change, and there are many similar examples. Resistant varieties should be developed to avoid further yield losses.
- *Resilient ecosystems.* Improving ecosystem management and biodiversity can provide a number of ecosystem services, which can lead to more resilient, productive, and sustainable systems as climates change. These services include control of pests and disease, regulation of microclimate, decomposition of wastes, regulation of nutrient cycles, and crop pollination.
- *Genetic resources.* Genetic makeup determines tolerance to shocks such as temperature extremes, drought, flooding, pests, and diseases. It also regulates the length of the growing season or production cycle and response to inputs such as fertilizer, water, and feed. Preservation of genetic resources of crops and their wild relatives is fundamental in developing resilience to climate shocks, improving the efficient use of resources, shortening production cycles, and generating higher yields (and quality and nutritional/energy content) per area of land.
- *Harvesting, processing, and supply chains.* Efficient harvesting and early transformation of agricultural produce can reduce post-harvest losses and preserve crop quantity and quality. It also ensures better use of co-products and byproducts as livestock feed, to produce renewable energy in integrated systems, or to improve soil fertility.

Specific adaption measures for climate-resilient agricultural systems include expansion of rainwater harvesting, water storage and conservation techniques, water reuse, desalination, water use and irrigation efficiency, adjustment of planting dates and crop variety, crop relocation, and improved land management (erosion control and soil protection through tree planting).

Sources: Food and Agricultural Organization of the United Nations (FAO). 2010. *Climate-Smart Agriculture: Policies, Practices and Financing for Food Security, Adaptation and Mitigation;* Glantz et al. 2009. *Coping with a Changing Climate: Considerations for Adaptation and Mitigation in Agriculture.* Food and Agricultural Organization of the United Nations (FAO); and Bogdanski, A. et al. 2011. *Making Integrated Food-Energy Systems Work for People and Climate: An Overview.* Food and Agricultural Organization of the United Nations, Rome.

Adaptation Measures for Geothermal Energy

In general, no specific adaptation measures are required for geothermal power systems. If cooling water is restricted with climate change, air-cooled systems could be used (Table 10), although it may be less expensive to develop new water sources. Geothermal infrastructure, like any other, may need greater protection where floods are likely to increase.

Table 9 Key Climate Change Impacts and Adaptation—Biomass Energy and Biofuels

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Floods/ precipitation	• Biomass supply • Turbine/ generator	• Land degradation/erosion with possibly lower fuel supply and less electricity output	• Soil and nutrient management • Improved water harvesting and use • Resilient ecosystems • Use of trees and shrubs in agricultural systems to improve soil fertility and soil moisture through increasing soil organic matter.
Precipitation or temperature changes	• Biomass supply • Turbine/ generator • Boiler and boiler water treatment system • Fuel feed system • Ash handling and air pollution control systems • Cooling tower	• Temperature and rainfall changes could increase or decrease electricity output depending on feedstock productivity. • Higher rainfall can increase moisture content of feedstock, lowering energy content. • Changing precipitation patterns could affect availability of freshwater for cooling.	• Expansion of rainwater harvesting, water storage and conservation techniques, water reuse, desalination, water use and irrigation efficiency, adjustment of planting dates and crop varieties, crop relocation, and improved land management • Use of salt-tolerant plants (halophytes) or robust crops with high biological heat tolerance and water stress tolerance • Flood protection improvement • Expansion of irrigation systems or improvement of the efficiency of irrigation
Extreme events	• Feedstock and infrastructure	• Possible damage to fuel supplies and generation infrastructure	• Increase the robustness of biomass power plants • Behavioral adaptation measures including early warning systems for rainfall and temperature anomalies, support for emergency harvesting for an imminent extreme event, and provision of crop insurance systems

Table 10 Key Climate Change Impacts and Adaptation—Geothermal Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Temperature increase	• Production and injection wells • Power plant and cooling systems • Pipeline system	• Will decrease air and underground differential and could affect power output	• If cooling water is unavailable with climate change, air-cooled systems could be used.
Extreme events		• Might damage infrastructure	• Geothermal infrastructure, like any other, may need greater protection where floods are likely to increase.

2.10. Ocean Power

Vulnerability of Ocean Energy to Climate Change

Energy from the ocean—sea wave and ocean thermal energy conversion (OTEC)—is primarily exploratory in nature and not yet commercialized. Energy from tidal flows can be considered commercial, but is a niche hydropower technology with limited practical application. However, there is considerable development of sea wave technologies, some of which can be considered near commercial (UK government 2011), tidal energy is under construction in Asia, and OTEC could eventually provide substantial amounts of electricity (and potable water) in coastal tropical locations and in island communities with very limited energy supply options. All could be impacted by climate change and are considered briefly in this report.

Sea wave. There were only 2 MW of installed sea wave capacity in International Energy Agency member countries by the end of 2010 (IEA 2011a). Ocean waves carry substantial energy, more than 50 kW/meter of wave front offshore of Scotland (Harrison and Wallace 2005), and although driven by wind, are generally more predictable than the wind. In the Pacific island DMCs, measurements indicate a lower typical energy density of 10–30 kW/m, which is still substantial, with the resource increasing with distance from the equator (Wade and Johnston 2005). Sea wave technologies are sensitive to changes in wind patterns that alter wave regimes (Harrison and Wallace 2005, 2005a). Although they are engineered to withstand rough weather, extreme waves and cyclones are serious risks, especially for those anchored or built onshore. Among the components vulnerable to increased risk of damage due to extreme winds and waves are the wave energy converter, cables and connectors to the seabed, mooring spars and floats, anchoring, seabed transformers and switchgear, and the power cable to shore (Halloran 2010). The following changes to climate can also damage onshore or nearshore sea wave systems (Hemer et al. 2008):

- coastal inundation during severe storm events through the combined effects of sea level rise, storm surge, and ocean waves;
- chronic coastal erosion brought about by large wave events, or changes in wave direction shifting coastal sand and sediment; and
- seabed disturbance impacting subtidal habitats and seabed structures or power lines.

Tidal. The only commercial tidal energy technology[18] is the barrage system. At the end of 2010, there were 265 MW operating, expected to nearly double by 2012 with the completion of Korea's Sihwa plant (IEA 2011a). With barrage technologies, the tide fills a natural or artificial basin, with the opening blocked at full tide. As the tide retreats, the difference between the water levels inside and outside the basin is used to drive a standard low-head turbine. Barrage tidal power is highly predictable but unsuited for baseload operations since tides reverse twice a day; when inlet and outlet heights are the same, no power can be generated. Tidal energy systems face much the same vulnerabilities to climate change as sea wave energy. Concerns include floods and storm surges, which could damage infrastructure. If sea levels rise, the available head would decrease and less power would be produced.

Ocean thermal energy conversion. OTEC technology is extremely complex and unproven; no commercial OTEC plants have been built or operated. There is considerable energy potential for tropical offshore systems as well as for onshore systems where there is a steep drop to ocean depths. OTEC exploits the thermal difference between the warm ocean surface and the cold deep water, typically 20°C at a depth of 1,500 m in tropical oceans. With such a small temperature differential, OTEC is inefficient for electricity production, requiring the circulation of large amounts of cold and warm water to produce a significant output. There is cogeneration potential that could add to OTEC's economic viability: seawater desalinization, mariculture, liquid hydrogen fuel production, and seawater air conditioning. Although OTEC systems could be constructed on reefs with a rapid drop to the deep ocean, most would

[18] There are also prototype tidal stream systems (Denniss 2009) with only 4 MW installed (IEA 2011a).

probably be offshore, where underwater power lines could be damaged in extreme weather conditions (Plocek and Laboy 2009). Salinity, sea level, wind patterns affecting wave production, and intensity and frequency of extreme weather events could all have an impact on energy production (Wilbanks et al. 2008).

The environmental impact of moving huge quantities of cold nutrient-rich waters to the surface is unknown but potentially serious. About 3–5 m^3/sec of warm surface water and a similar amount of cold deep water are required for each MW of power generated (NOAA 2010), equivalent to 20–35 million m^3 daily for a 40-MW system. Discharging used cool deep seawater would cause nutrient redistribution and increased biological productivity, which could be exacerbated by higher surface and deep ocean temperature differentials. However, an increase in sea surface temperature and temperature gradient might increase the efficiency of energy production.

Adaptation Measures for Ocean Energy

Adaptation measures to improve the resilience of sea wave system to climate change include the following (Hayward and Osman 2011):

- Devices need to be engineered to withstand extreme waves by being massive or alternatively inexpensive enough that the financial loss is not too great.
- Consider onshore or nearshore systems, which are less vulnerable to storm damage (although the power available is less than that further out at sea).
- For floating systems, consider designing for 50-year freak waves (with an amplitude about 10 times the average wave with 100 times the wave energy).
- To reduce vulnerability to severe stresses on anchorage systems, design them to be oriented in the wave direction rather than across the wave front.
- Consider protection mechanisms against storm surges such as automated lowering of expensive components to the sea floor, designing devices to be sufficiently seaworthy to cope, or disconnecting or shutting down devices so they are not operating during extreme events.

Adaptation measures are much the same for tidal and OTEC systems. For OTEC, if ocean wind speeds and waves or extreme events are expected to increase significantly, it may be necessary to design the deep-sea pipes to withstand greater stresses. Table 11 summarizes climate change impacts and adaptation measures for ocean energy systems.

3. Transmission and Distribution

Vulnerability of Transmission and Distribution

Transmission and distribution (T&D) networks typically have a lifetime of 30 to 50 years and have usually evolved on an ad hoc basis, rather than been optimized to current generation and load profiles.[19] In the United States, about 40% of the total capital asset base of the electricity system is in T&D (IEA 2010), which is approximately the percentage of T&D investment in the power sector expected to be required in Asia between now and 2030 (APERC 2009). New T&D investments tend to be permanent, often due to land access issues, underlining the importance of decisions made now to adapt to potentially disruptive impacts of future climate change.

If a single power plant fails, others can fill the gap, but alternative T&D network routes are often unavailable. Moreover, supply and demand must be balanced, excessive voltages and frequency fluctuations must be avoided, and the systems should not pose a threat to health, safety, or the environment. This means that operating temperatures must be kept at safe levels, grids should not be interrupted, and distances from trees, people, and buildings should be kept at safe levels (European Commission 2011). Distributed generation technologies, control systems, and many efficiency measures rely on a stable grid connection. Table 12 summarizes a range of climate change impacts on T&D networks.

[19] A load profile is the variation in power demand versus time, usually shown graphically. It varies according to customer type, day of the week, ambient temperature, and holiday seasons. The profile can change very significantly over time.

Table 11 Key Climate Change Impacts and Adaptation—Ocean Power

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Sea Wave			
Wind speed and extreme wave heights	• Onshore generation systems • Offshore generation systems • Undersea anchoring, transformers, and power cables	• Severe damage or destruction to infrastructure	• Devices need to be engineered to withstand extreme waves. • Consider shore-based or nearshore systems, which are less vulnerable to storm damage. • For floating systems, consider designing for 50-year freak waves (with amplitude ~10x the average wave but 100 x the energy). • Consider protection against storm surges such as automated lowering of expensive components to the sea floor, designing the device to be sufficiently seaworthy to cope, or disconnecting or shutting down devices so they are not operating during extreme events.
Extreme events (storm surge)		• Coastal inundation • Damage to seabed structures or cables	• As above • Design anchorage systems to be oriented in the wave direction rather than across the wave front.
Tidal Energy			
Sea level rise	• Barrage systems: – Sluice gates – Turbine	• Possible reduced energy output	• Raise level of barrage basin walls.
Storms/extreme events		• Damage to infrastructure	• Design more robust systems.
Ocean Thermal Energy Conversion			
Temperature increases	• Pumps • Heat exchangers • Turbine	• Higher sea surface temperature could – increase power output (if surface/deep sea ΔT increases) and – increase nutrient dispersal.	• Construct larger pipes to increase volume of water to the surface.
Extreme events	• Pipes extending to 1,500 m depth or more • Onshore facilities (if any) • Undersea power cables	• Extreme events could damage surface or undersea infrastructure (e.g., dislodge deep sea water pipes).	• See sea wave energy systems above. • Design deep-sea pipes to withstand greater stresses.

ΔT = change in temperature, m = meter

Sources: Hemer, M.A. et al. 2008. *Variability and Trends in the Australian Wave Climate and Consequent Coastal Vulnerability*. Commonwealth Scientific and Industrial Research Organisation, Australia; and Halloran. N. 2010. *Design Challenges for Wave Energy Projects.* www.seai.ie/Renewables/Ocean_Energy/Ocean_Energy_Information_Research/Ocean_Energy_Publications/OE_O_and_M_Workshop/Noel_Halloran_TFI.pdf

Table 12 Impacts of Climate Change on Electricity Transmission and Distribution Networks

Climate Variable	Physical Components	Key Impacts	Adaptation Options	Level of Impact
Wind speed and storms	Wind and storm damage	Overhead lines Pylons	Variable	Variable from moderate to high
	Increasing heat convection	Overhead lines	Continuous	Up to 20% capacity increase for each m/s rise in wind speed
Increasing temperature	De-rating	Transformers	Continuous	–1% load per 1°C rise
	Decreased conductivity	Overhead lines Underground cables	Continuous	Resistance rises ~0.4% per 1°C degree rise –0.5 to –1% line load capacity per1°C rise
	Sag	Overhead lines	50°C	4.5 cm per 1°C rise*
	Thawing permafrost	Substations Pylons	Varies with local conditions	Potential total loss of supply locally
Increasing drought	Moisture migration	Underground cables	>55°Cat cable surface	Reduces cable capacity by 29%
	Dry soil movement	Underground cables	Variable	Repair cost roughly $4,200 per fault
Flooding	Inundation	Substations	Varies with local conditions	Up to 100% loss of supply locally
	Cable breakage	Underground cables	As above	As above

cm = centimeters, m/s = meters per second

*at conductor surface for 35°C ambient temperature and span of 400 meters

Source: European Commission. 2011. *The Impact of Climate Change on Electricity Demand.* www.adamproject.eu

Increasingly variable weather and potentially stronger storms would affect the integrity of T&D lines and equipment in various ways:

- Strong winds (over 100 km/hour) can damage electric wires and other distribution components (Contreras, Lisperguer and de Cuba 2008), mostly to the distribution systems through tree damage, with transmission much less affected (Ward 2010).
- Provided they remain below damage levels, stronger winds cool overhead lines by increasing heat convection. Lines can then carry a larger electric load while staying within temperature limits, which is usually 80°C at conductor surface (European Commission 2011).
- The networks, including transformer and switching stations, can be affected by heavy snow, ice, and moisture (Rothstein and Halbig 2010). Line integrity can be reduced (World Bank 2008) due to line sag.
- Transmission lines with capacity constraints can suffer from load management issues, particularly during summers and winters when the demand for cooling and heating are at their peak, decreasing the amount of power that can be delivered through the network (ESMAP 2009, Aguiar et al. 2002).
- T&D infrastructure can suffer from increased risks of flooding, landslides, and other natural hazards, with equipment mounted at ground level in substations especially susceptible.
- High temperature limits the power rating of overhead lines, underground cables, and transformers but does not cause immediate faults (Ward 2010). Network losses can increase by 1% if temperature increases 3°C in a network with

initial losses of 8% (European Commission 2011).

- During extended periods of heat and drought, dust can build up on conductors. Lighting can also affect reliability (EPRI 2008).

Although it is not a direct effect of climate change, T&D grid control systems, and therefore power distribution to consumers, become more vulnerable to failure as higher percentages of renewable energy are fed into grids. Increasingly, grid control is part of the broader information and communication technology (ICT) system. Reliable ICT is critical to power sector operations both at individual generation facilities and more generally for forecasting and routing of electricity through the T&D networks. With increased renewable energy in the grid, whether large scale or through smaller-scale localized generation, input-load balance and stability become more difficult. Real-time monitoring is required to allow peaks and troughs in demand to be accurately forecast. Understanding the vulnerability of ICT to indirect climate change impacts is therefore important for the energy sector (URS 2010).There are also more direct impacts. Wireless transmission especially can degrade with high temperature and is also vulnerable to subsistence, storms, and intense precipitation. Copper and fiber-optic cables used in ICT systems are at risk from increased flooding and/or erosion (UK Government 2011).

Adaptation Measures for Transmission and Distribution

Improving the resiliency of electricity infrastructure involves preparing T&D systems to continue operating despite damage. Adaptation efforts should also increase the system's ability to return to normal operations rapidly if outages do occur. Specific measures include the following:

- Reinforce existing T&D structures and build underground distribution systems (Neumann and Price 2009).
- Require higher design standards for distribution poles (usually wood) and towers (steel).
- Change routes of overhead lines along roads away from trees, rigorously prune trees, and use covered and/or insulated conductors and more underground cables, especially in wooded areas.
- Where higher temperatures may occur, specify more effective cooling for substations and transformers, including retrofitting measures, improved shading, and choice of cooler locations where possible.
- Where lightning strikes may increase, include lightning protection (earth wires, spark gaps) in the distribution network.
- Design more flexibility into T&D networks, allowing increased rerouting during times of disruption.
- Forbid the construction of power lines near dikes and ban "permanent" trees such as eucalyptus and melaleuca next to existing dikes, as Cho Moi district of Viet Nam's An Giang Province has done to ensure an easy option of raising the height of dikes if needed in the future (Dobes 2010).
- Design improved flood protection measures for equipment mounted at ground level in substations.
- Where stronger winds are expected, strengthen distribution poles with guy wires (USDOE 2010).
- Increased pressure on the grid, whether or not it is climate-induced, can also be reduced through distributed, decentralized energy generation, although care must be taken to maintain grid stability as increased percentages of wind or solar energy are fed to the grid.
- Invest additional resources into building a resilient, high-capacity transmission system, which is required in any case to handle more renewable energy.[20]

- Protect masts, antennae, switch boxes, aerials, overhead wires, and cables from precipitation (water ingress, snow melt); wind; snow (weight); unstable ground conditions (flooding, subsidence); and changes in humidity (Horrocks et al. 2010).

[20] A 2002 UK study (IEA 2010) concluded that wind power supplying 20% of total demand would require transmission investment 6% higher than current annual capital expenditure in the grid, rising to 17% for a 30% wind contribution.

- Use "smart transformers," which control the flow of electricity to stabilize existing, aging power grids (Freedman 2011). Modern transformer designs can also reduce losses by up to 80% and handle a wider range of ambient conditions. Globally, network losses range from 4%–27%, of which a third typically occur in transformers and 70% in the distribution system (Targosz 2005).
- Consider improved system management through investing in "smart grids"—the use of smart meters and other digital technology meant to allow better consumer and utility management of energy. These have been overhyped but might improve reliability, power quality, efficiency, information flow, and improved support for renewable and other generation technologies over time (Makovich 2011).
- Specify ICT components that are certified as resilient to higher temperatures and humidity and design improved redundancy into ICT systems, including wireless transmission better able to handle high temperatures. More resilient ICT systems will be even more important as smart grids are implemented widely.

Key climate change impacts on T&D networks and adaptation options are summarized in Table 13.

4. Electricity End Use

Vulnerability of Electricity End Use to Climate Change

The literature on patterns of likely energy end use under a changing climate focuses almost entirely on the effects of temperature change. Hotter summers increase the demand for cooling,[21] resulting in higher peak demand. Empirical studies unsurprisingly suggest that in warm climates, energy demand will increase in the spring and summer (de Cian et al. 2007). In moderate or temperate climates, as temperatures rise, demand will increase in warm months but decrease in the winter (Box 13).

A study in Thailand, using a range of socioeconomic scenarios, also suggests increases in future electricity demand if expected climate changes occur. A temperature increase of 1.7°C –3.4°C by 2080 will increase peak electricity demand by 1.5%–3.1% in 2020, 3.7%–8.3% in 2050, and 6.6%–15.3% in 2080, even assuming no change in saturation of air conditioning, requiring a large investment in additional peak and base load capacity and transmission capacity. Energy efficiency initiatives were not assessed but were assumed to be able to significantly change the demand profiles (Parkpoon and Harrison 2008).

Buildings account for about 40% of the world's energy use (WBCSD 2009) and a higher percentage for electricity, with space cooling, refrigeration, and lighting accounting for the bulk of electricity use. Energy loads such as space heating, cooling, and lighting are intrinsically related to building design and construction, and are best (or must be) addressed during design and construction (Liu et al. 2010). One recent study (Cullen et al. 2011) calculates that, theoretically, implementing the best available design improvements to passive systems in every building, factory, and vehicle would reduce world energy demand by 73%. With additional gains from energy-efficient active systems such as light bulbs, appliances, and engines, as much as 85% of energy demand could vanish. Although this is impractical in practice, there is a great deal of opportunity to adapt to climate change by reducing demand, thus requiring less investment in generation and distribution systems.

Adaptation Measures for Electricity End Use

Adaptation measures to cope with increased energy demand with temperature rises are of three types: (i) simply increasing generation (MWh) and capacity (MW) to meet increased demand (business as usual approach); (ii) improving the efficiency of energy supply (generation, transmission, distribution system

[21] Future changes in cooling demand are likely to depend upon many factors including changes in building stock, changes in the uptake of cooling systems, population size, and behavioral change in addition to changes in climate.

Table 13 Key Climate Change Impacts and Adaptation—Electricity Transmission and Distribution

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Temperature increase	• Transmission and distribution cables • Substations (infrastructure, switching gear, etc.) • Transformers	• Can reduce electricity carrying capacity of lines • Can increase losses within substations and transformers.	• Specify more effective cooling for substations and transformers. • Specify certified ICT components that are resilient to higher temperatures and humidity.
Precipitation and flooding	• Transmission towers • Distribution cables (if underground) • Substations (infrastructure, switching gear, etc.) • Transformers	• Heavy rains and flooding can undermine tower structures through erosion. • Snow and ice can damage T&D lines through sagging. • Drought can increase dust and lightning damage. • Flooding can damage underground cables and infrastructure in general.	• Build a resilient high-capacity transmission system. • Design improved flood protection measures for equipment mounted at ground level in substations. • Forbid the construction of power lines near dikes and ban “permanent” trees next to existing dikes. • Protect masts, antennae, switch boxes, aerials, overhead wires, and cables from precipitation (water ingress, snow melt); wind; snow (weight); unstable ground conditions (flooding, subsidence); and changes in humidity.
High wind speeds	• Transmission and distribution cables • Towers (pylons) and poles	• Strong winds can damage T&D lines.	• Reinforce existing T&D structures and build underground distribution systems. • Require higher design standards for distribution poles.
Extreme events (flood, typhoons, drought)	• Substations (infrastructure, switching gear, etc.) • Control/ICT systems • Transformers	• High temperatures, storms, erosion, or flooding can damage control systems through loss of ICT service or reduced quality of service.	• Increase the system’s ability to return to normal operations rapidly if outages do occur. • Change routes of overhead lines along roads away from trees, rigorously prune trees, use covered and/or insulated conductors, and use more underground cables, especially in wooded areas. • Increase decentralized energy generation (with less T&D grid requirements). • Allow increased rerouting during times of disruption. • Include lightning protection (earth wires, spark gaps) in the distribution network. • Design redundancy into ICT systems. • Develop and use “smart transformers” and “smart grids.”

ICT = information and communications technology, T&D = transmission and distribution.

Box 13 Effects of Temperature Increase on Electricity Demand

Based on a medium emissions scenario through 2100, energy use modeling for southern European cities suggests an increase over time in cooling and a decrease in heating demand, resulting in a net overall increase in electricity use, likely to be 10% in Greece and 19% in Turkey (Eskeland and Mideska 2010). However, electricity consumption changes due to temperature change are expected to be small compared with those due to changes in income, demography, and technology. For Europe overall, the estimated changes in consumption caused by temperature change is 0.3 kWh per year per capita for a unit (a unit = 1°C change for one day) of temperature increase and 1.2 kWh per year per capita per unit of temperature decrease (European Commission 2011).

Electricity demand per capita in California has remained nearly flat over the last few decades, partly due to energy efficiency incentives, but electricity used for summer cooling increases almost linearly with higher temperatures. Even ignoring population growth and a larger market for air conditioning, there could be a 17% electricity deficit in California in coming decades due to electricity demands during periods of extreme heat (i.e., 90% probability of exceeding the warmest summer days under the current climate), which are expected to double from 12 days per summer to 23–24 days between 2005 and 2034 (Miller et al. 2007). For the US overall (USDOE 2007), a large number of studies suggest a decrease in energy use for residential and commercial heating of 9.2% for each 1°C rise and an increase of 10%–15% per 1°C in cooling demand (cooling, unlike heating, is entirely through electricity). Maximum power demand (MW) also increases with temperature, but the percentage change varies considerably by region.

improvements); and (iii) improving end-use efficiency. There has been a fairly steady improvement in energy efficiency since about 1980, and this can be expected to improve further even without policy interventions (Warde 2007), although energy consumption is likely to continue to increase considerably. However, adaptation measures specifically for climate change-induced demand can have substantial impacts.

In California, for example, adaptation could reportedly reduce projected increases in electricity demand by roughly one-third for inland cities by 2100, and by as much as 95% for cooler coastal cities (Miller et al. 2007). A recent study in India suggests a continuation of past growth patterns in which growth in electricity demand exceeds supply, even in the absence of climate change. Sathaye and Gupta (2010) claim that cost-effective end-use efficiency measures have the potential to eliminate the expected electricity deficit by 2014 while requiring less investment for new power supply compared with a “business as usual” scenario. Because of rapid growth in Asia, restricting appliance sales to efficient products can make a significant difference fairly quickly. Air conditioner sales, for example, are growing at 25% per year in India and vary widely in energy use. Even with cooling fans, efficient models can provide more than 27% energy savings.

Supply-side adaptation measures have been covered in previous sections of this report. There is also a large range of technical and policy demand-side energy efficiency measures available that can reduce energy demand and the need for investing in new capacity, thus indirectly reducing the impacts of changes in climate or increased variability in weather. These are evolving rapidly and are only briefly touched on. Many may require new regulations and their enforcement to have a discernible impact and may be more effective if power utilities are required to take a proactive role in demand-side management. Policy measures,[22] which can make economic sense even in the absence of climate change, include the following:

[22] The European Union-supported Climate Parliament describes 22 separate areas of energy efficiency policies with examples of savings achieved at www.climateparl.net/cp/99.

- Require minimum energy performance standards for new commercial buildings and a wide range of electricity-using appliances (beginning with air conditioning, lighting,[23] and office equipment), with labeling and certification programs for both buildings and key appliances.
- Require and enforce energy performance standards (including maximum allowable "phantom loads" for chargers, power bricks, set-up boxes, TVs, etc.), whether manufactured locally or imported.
- Develop legislation and access to finance for energy service companies, with remuneration based on energy actually saved through an investment, reducing the risks of undertaking energy efficiency initiatives and measures.
- Set minimum standards for industrial electrical motors.
- For households, consider subsidized programs for mass replacement of incandescent lights with far more efficient compact fluorescent lights (CFL) or, soon, light-emitting diodes (LEDs) and replacing old inefficient refrigerators with newer efficient models.
- Adopt the International Organization for Standardization (ISO 2011) global energy management standard (ISO 50001) released in mid-2011, a transparent framework for integrating energy efficiency into an organization's management practices that can be used to evaluate and implement energy efficiency initiatives, as well as to benchmark and document energy savings for compliance.
- Consider evaporative cooling, which may be effective even in temperate climates as temperatures rise and summers become hotter and drier (Smith et al. 2011).
- Consider the possible impact of solar photovoltaic systems on cooling. Rooftop panels can reduce summer building cooling loads by nearly 30°C, typically saving 5% of cooling energy (Dominguez 2011). Simply installing highly reflective roofs can reduce summertime air conditioning energy and peak demands of commercial buildings by 10%–30% in warm weather or mild climates (Levinson and Akbari 2009).

New buildings are likely to last 100 years or more and may need to function under conditions of considerable climate change. Designers and developers should maintain an awareness of new and emerging technologies that may soon be commercialized. These include new small absorption chilling systems for refrigeration and air conditioning using relatively low-temperature heat from waste or solar water heating (Bullis 2011). A report to the California Energy Commission profiles international developments for emerging energy efficiency technologies globally based on high-potential energy savings, lower initial costs relative to existing technologies, and other significant benefits. These include a range of industrial and agricultural refrigeration and cooling systems with the potential for improvements of up to 30%; thermal cooling using renewable energy; and variable-speed drive controls, which could reduce power for fans, pumps, and blowers by up to 60% (Xu 2009). Evaporative cooling has long been used in hot, arid regions and may be effective even in temperate climates as temperatures rise and summers become hotter and drier (Smith et al. 2011).

Some key impacts of climate change on energy end-use demand and adaptation options are summarized in Table 14.

[23] Asia is the world's largest market for general lighting (which accounts for 75% of the global lighting market) and is expected to account for 45% of global lighting demand by 2020. Globally, incandescent lights account for 52% of the 2010 market in terms of units sold. Countries that don't ban inefficient lights or differentiate on taxes or duties could lose the efficiency benefits as cheaper, less-efficient lighting continues to be manufactured or imported (McKinsey 2011).

Table 14 Key Climate Change Impacts and Adaptation—Electricity End Use

Climate Variable	Physical Components	Key Impacts	Adaptation Options
Temperature, solar radiation, and humidity	• Building design	• Increased energy demand: » Higher summer temperatures increase cooling loads. » Colder winter temperatures (which may occur in some locations despite overall warming trend) increase heating loads.	• Require minimum energy performance standards for new commercial buildings and key electricity-using appliances (lighting, air conditioning, refrigeration) with labeling and certification programs for both buildings and key appliances. • Develop legislation and access to finance for energy service companies for efficiency improvements. • Consider mass replacement of incandescent lights with far more efficient compact fluorescent lights, or soon, light-emitting diodes (LEDs). • Adopt ISO 5000, a global energy management standard. • Consider evaporative cooling or absorption chilling systems.
	• Air conditioning & heating systems	• As above	• As above: require and enforce minimum energy performance standards.
	• Generation and T&D grids	• Increased climate-induced electricity demand requires larger investment in generation and grid systems to cope with increased energy use (MWh) and higher peak demand (MW).	• Increase generation (MWh) and capacity (MW) to meet increased demand. • Improve supply-side efficiency (broad range of generation, transmission, distribution system improvements).

MW = megawatts, MWh = megawatt-hour, T&D = transmission and distribution

5. Summary of Findings and the Way Forward

Important findings presented in this paper are summarized below:

- Countries in Asia and the Pacific are highly exposed to climate change and vulnerable to its impacts, with nine or more DMCs believed to be at extreme risk. Of the world's six most rapidly growing cities recently classified to be at the most extreme level of risk, five are ADB DMCs.
- Projected climate change is expected to significantly affect the entire energy sector: fuel mining and production, fuel transportation to power plants, electricity generation, high voltage grid transmission, low voltage distribution to consumers, and patterns of energy load growth and end-use demand.
- Much of the energy infrastructure in Asia and the Pacific is located where weather and climate may become increasingly variable. Energy is thus a vulnerable sector in a highly vulnerable region, with a degree of vulnerability not generally appreciated.
- There is a great deal of practical information on the effects of specific climate variables—wind, temperature, humidity, etc.—on the operations of specific energy technologies, but only limited experience on impacts at the project level (i.e., for specific climate and weather variables at specific sites).
- The most severe impacts are likely to be those from (i) flooding for a wide range of generation

technologies and those in low-lying areas, (ii) insufficient water for effective cooling in areas of increasing drought or lower water availability, (iii) high air temperatures and more severe storms for T&D grids, (iv) storms for ocean-based energy generation, (v) heat waves for energy end use, and (vi) sea level rise for energy generation and distribution in general in low-lying areas. There are also a number of technology-specific vulnerabilities and impacts.

- Electricity demand in Asia is growing rapidly, with a projected average increase of about 3.4% annually through 2030. Meeting this level of demand will require an investment of roughly \$3.3–\$4.6 trillion (in constant 2006 dollars) between 2006 and 2030. This is on the order of \$160 billion per year, of which about 87%, or \$140 billion, is expected to be required in the DMCs.
- There has been considerable attention on ways to mitigate the effects of energy production on the earth's climate but much less on adapting the energy sector in the region to projected changes in climate. Given the huge required investments in coming decades (estimated to reach \$3.3–\$4.6 trillion in constant 2006 dollars by 2030) and the decades-long operating lives of energy systems, these investments should fully account for climate change and, where cost-effective and practical, adopt approaches that are resilient to these projected changes.
- There is a wide range of adaptation opportunities that can improve power sector climate change resilience and ADB has carried out adaptation analyses for a number of proposed and approved projects. This has included vulnerabilities, expected impacts, and likely costs and benefits of adaptation. In some cases, small additional costs at the development and design stages are expected to result in substantial net benefits.
- Impacts can be costly, but a wide range of adaptation options exist that can be implemented at different stages of project implementation. These measures can generally be divided into engineering and non-engineering options:
    - » Engineering measures include more robust designs in general; decentralized generation systems to spread risks; components certified as humidity-, salt-, and and/or temperature resilient; air or low-water cooling systems; redundancy in control systems; improved supply-side and end-use efficiency; and a range of technology-specific adaptations.
    - » Non-engineering measures include more robust O&M procedures; land rezoning to restrict future investments to less vulnerable locations; decentralized local planning; integration of adaptation and mitigation planning; integration of climate change and disaster management planning; improving forecasting of supply and demand with climate change; integrating power sector planning with that of water supply and other sectors; and improving localized models used to predict storms and flood hazards.

In a number of circumstances, the costs of inaction, or poorly considered and badly executed actions, are expected to be far higher than well-planned and implemented efforts to improve energy sector resilience to climate change. Inadequate attention to these impacts can increase the long-term costs of energy sector investments, the likelihood that they will not deliver intended benefits, and the probability of eventual failure under climate stress.

- It may often be appropriate to promote no-risk or low-risk adaptation strategies that deliver development benefits at low cost regardless of the nature and extent of changes in climate (e.g., where uncertainty regarding climate change is high, and where large climate-proofing capital investments cannot be easily justified). In other circumstances, large climate-proofing investments may be justified. A "do nothing" response may occasionally be appropriate and cost-effective.

Table 15 illustrates some possibly severe impacts of climate change for different locations and energy technologies. It is only meant to be a broadly indicative summary and does not attempt to be complete.

Table 15 Indicative Impacts of Climate Change on Electricity Generation, Transmission, and End Use

Technology	Δ Air Temp	Δ Water Temp	Δ Water Availability	Δ Wind Speed	Δ Sea Level	Floods	Heat Waves	Storms
Coal	1	2	1-3	-	-	3	1	-
Oil	1	2	1-3	-	-	3	1	1
Natural gas	1	2	1-3	-	-	3	1	1
Nuclear	1	2	1-3	-	2*	3	1	-
Hydropower	-	-	1-3	-	-	3	-	1
Wind	-	-	-	1-3	3*	1	-	1-3
Photovoltaic	1	-	-	1	-	1	1	1
CSP/solar tracking	-	-	2	2	-	1	1	2
Biomass/biofuel	1	2	2	-	3*	3	1	-
Geothermal	-	1	-	-	-	1	-	-
Ocean	-	1	-	-	1	N/A	-	3
T&D grids	3	-	-	1	3*	1-2	1	2-3
End use	2	-	-	-	-	-	3	-

Δ = change in, CSP = concentrating solar power

*Higher severity in coastal or low-lying areas

Notes: 3 = severe impact, 2 = medium impact, 1 = limited impact; – = no significant impact, N/A = not applicable

Source: Modified and expanded from European Commission. 2010. *Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change*. Final report. European Commission Directorate-General for Energy Report EUR 24769.

There are clear benefits to the DMCs from considering climate change vulnerability and likely climate change impacts at the project level before finalizing engineering designs for energy investments. There are, however, some constraints that need to be addressed to improve the practicality of incorporating climate change considerations into project designs and evaluating the costs and benefits of adaptation measures. Some key constraints, and the way forward in addressing them, follow:

- Only a few studies have been carried out on the implications of climate change on proposed energy investments at the project level. A practical knowledge base is needed of threats, impacts, adaptation costs, adaptation benefits, and experiences in designing and implementing adaptation measures into energy sector projects. This should be developed, with climate analysis required for all proposed projects of a specified minimum size or located in any area of probable extreme risk.
- Much of the available information on vulnerability is based on large-scale observations and measurements. The models in the IPCC’s Fourth Assessment Report (IPCC 2007) use horizontal grid cells that are about 100 by 150 km across at mid latitudes, or an area of 10,000 km^2 or more. This is generally inadequate for project-level analysis but large-scale models can be downscaled to simulate local climate processes. More downscaling, and consideration of

appropriate downscaling techniques suitable for energy sector investment decisions, is required.[24]

- The capacity of models to predict storms and map their tracks accurately is limited. Modeling needs to improve to more accurately assess the risks of extreme weather events.
- In brief, a key constraint is identifying likely changes in climate variables at the local level and the physical impacts of these changes on energy infrastructure and on the provision of energy services provided by that infrastructure. This uncertainty increases the need and importance of strong technical and economic analysis and the appropriate tools for the analysis.
- If climate change impacts are quantitatively identified, the economic analysis of climate-resilient investment options is relatively straightforward. However, the present value of expected costs and benefits of that investment using the discount rates required by development banks will often lead to the conclusion that climate change may not really matter unless the projected impacts are very large. Additional noneconomic tools for assessing the pros and cons of climate-resilient approaches to energy sector investments, and safeguarding these investments, are needed.

- Accurate weather and climate data, both past and projected, are necessary for good energy sector (and of course broader) decision making. Data and the information they contain are costly to collect, archive, and distribute, and accessing data linking weather and climate with the energy sector can be problematic, particularly at regional or local scales. Fewer data are being archived than in the past for the public good as national meteorological and hydrological services are increasingly commercialized. Clear policies on the data, its availability, and sharing need to be developed to better adapt to climate change.[25]

[24] A study on the use of climate modeling for improving investment decisions about water utilities concluded that significant improvements to global climate models (GCMs) and regional climate models (RCMs) to the point where their output can be input directly into utility planning models without downscaling is expected to take more than a decade. In the meantime, “more extensive coordination among GCM, RCM, and statistical downscaling communities is needed to improve the usefulness of downscaled data” (Barsugli et al. 2009).

[25] Issues regarding climate and energy data are considered in Harrison and Troccoli (2010), who argue that data inadequacies are a serious issue that is certain to continue into the future.

Building Adaptation Strategies into Electric Power Sector Policy and Planning

A. Implications for Policies and Planning

Countries undertake policy processes in order to establish overarching frameworks for making decisions and setting priorities. Enhancing decision making by factoring in climate change risks will require a different process than for project-level interventions, where many key parameters are established, such as geographic location, scale, and technology. Therein lies a key difficulty with policy mainstreaming: merely mentioning climate change in policy documents does not necessarily result in effective action. In part, this is often because of lack of information about climate change, limited interministerial coordination (such as between meteorological focal points and energy focal points), weak implementation capacity and resources, and a lack of experience in designing and implementing climate change adaptation in both developed and developing countries.

For these reasons, many of the first climate change adaptation funds have advocated learning by doing or through pilot project initiatives. Establishing some implementation experience can inform the development of appropriate policy-level guidance. Another approach for developing policy experience that has been tested is policy-driven information gathering, or an explicit link between pilot project and policy mainstreaming. Adaptation strategies are tested and evaluated in the context of a given policy sphere and successful measures are fed back up into the policy. This integration can help improve the policy's general direction and achievement of its objectives.

B. National and Sector Policies and Processes

The Organisation for Economic Co-operation and Development (OECD 2009) identifies both national and sector levels as policy entry points that may be useful for adaptation mainstreaming. National policies and plans (note that in some countries the word policies is used while in others these are referred to as plans) include national visions, poverty reduction strategies, multiyear development plans, and national budgets. Sector development plans, such as transport master plans and their budgets, often flow from national plans and policies. Projects are then meant to be consistent with sector plans, and in some cases also national plans, particularly those that are cross-sector, regional, and of extremely high priority. Therefore, influencing these overarching frameworks can affect which projects are prioritized and the criteria they must meet in order to be financed.

The OECD guidance recommends two main sources of action for integrating adaptation at this level:

- *A clear recognition of climate risks and the need for adaptation within relevant national policies.* Incorporating climate change at this level can improve the likelihood that it filters down into sector plans and other levels of decision making. In the case of energy, and for infrastructure development generally, guidance intended to strengthen cross-sector cooperation between ministries can be very helpful. For instance, flood management around critical energy infrastructure can be better designed and implemented if coordinated among appropriate departments of meteorology, hydrology, and energy. Integrated planning around geographically vulnerable areas can produce high-quality development plans for disaster-prone areas (e.g., coastal areas). Moreover, climate change impacts are not set by national boundaries, and their effects may require regional coordination.
- *Applying a climate lens in the formulation of national policies and strategies.* A climate lens is an analytical process (or step, or tool) to examine a policy, plan, or program. It can be useful, for example, to identify areas of the country that are most vulnerable to climate change impacts and where priority actions can be directed (Box 14).

C. Electricity Sector Policies and Plans

Energy is fundamental to all aspects of development, so developing and implementing effective energy policies and plans involves a wide range of public and private actors in various sectors, even in the absence of climate change. More systematic approaches, and more effective coordination, will be necessary to cope with the uncertainty and potential impacts of climate change on the energy sector. Improved interaction is needed between those developing and implementing broad economic and development policies and energy-specific policies. Economic, financial, and broad governance policies and issues are often key drivers to energy supply and demand issues.

According to a recent World Bank study (Ebinger and Vergara 2011), mitigation is now a prime focus of many energy projects, but their search has failed to reveal many active energy sector programs or projects in which adaptation per se is recognized as a major management issue. At the regional and subregional levels in Asia and the Pacific, consideration of climate change issues is recognized as a necessary element

Box 14 Applying a Climate Lens

The application of a climate lens at the national or sector level involves examining

- the extent to which the policy, strategy, regulation, or plan under consideration could be vulnerable to risks arising from climate variability and change;
- the extent to which climate change risks have been taken into consideration in the course of program formulation;
- the extent to which the policy, strategy, regulation, or plan could lead to increased vulnerability, leading to maladaptation or, conversely, to missing important opportunities arising from climate change; and
- for pre-existing policies, strategies, regulations, or plans that are being revised, examining the nature of amendments that might be warranted in order to address climate risks and opportunities.

A rapid application of the climate lens should enable policy makers to decide whether a policy, plan, or program is at risk from climate change. If deemed to be at risk, further work would then be required to identify the extent of the risk, assess climate change impacts and adaptation responses in more detail, and identify possible recommendations.

Source: Organisation for Economic Co-operation and Development (OECD). 2009. *Integrating Climate Change Adaptation into Development Co-operation.* Paris: Organisation for Economic Co-operation and Development.

of energy policies and plans.[26] However, an analysis of 14 national energy policies and action plans for Pacific DMCs (Johnston 2010) that were prepared between 2003 and 2010 (but mostly 2005–2009), shows that most include only vague references to national climate policies and no explicit links to risk management or national disaster management plans. In several DMCs, climate and energy policies endorsed by governments were inconsistent. Only one national policy, adopted by the Marshall Islands in 2009, specifically requires the assessment of all new energy sector investments for climate change resilience or adaptation.

In December 2008 (ADB 2010a), the Government of Viet Nam approved the National Target Program to respond to climate change. In September 2011 (Government of Indonesia 2011), President Yudhoyono of Indonesia signed a decree requiring a national action plan within 12 months to substantially reduce greenhouses gas emissions in a number of sectors including energy. These decisions require the energy ministries to develop mitigation and adaptation action plans at both the sector level and, for large installations, the facility level. In these countries, and elsewhere in Asia and the Pacific, broad statements are in place or being developed to begin integrating climate change considerations within energy planning and policy, but thus far there is little detail on methods and approaches to evaluate risk and develop action plans.

Challenges faced by energy infrastructure with respect to climate change cannot be separated from the interactions between the built environment and the natural environment. Infrastructural changes that do not address some of the root issues—such as deforestation, land degradation, and water availability—will provide only a temporary and superficial fix. Energy planning ministries will need to coordinate more effectively with other line ministries and others in dealing with climate change issues. Options include the following:

- Establish or enhance cross-ministerial committees for managing adaptation to climate change, including ministries and departments dealing with overall energy policy, petroleum and gas, renewable energy, and energy-efficient transport.
- Strengthen the departments of environment, disaster risk management, and meteorology to improve and disseminate information on which to make decisions.
- Introduce early warning and response systems for energy ministries and power utilities to improve maintenance schedules and to respond quickly to post-disaster recovery needs.
- Promote no-risk and low-risk adaptation strategies that will have development benefits regardless of the nature and extent of climate changes. This is a useful and practical approach where uncertainty is high regarding climate change and where large capital investments cannot be easily justified.
- Incorporate climate change adaptation into energy investment environmental impact assessments (EIAs) and strategic environmental assessment guidelines, or preferably, as part of national EIA procedures.
- Integrate adaptation plans for energy and water into a joint strategy as the two are closely linked. Generally, the production and/or consumption of one resource cannot be achieved without making use of the other. Also, climate change affects the supply of both resources (Ebinger and Vergara 2011).

[26] See for example, the ASEAN Plan of Action for Energy Cooperation 2010–2015 (www.aseanenergy.org), the South Asia Regional Initiative for Energy's Regional Energy Policy Partnership (www.sari-energy.org), and the Framework for Action on Energy Security in the Pacific (www.spc.int/edd/en/download/finish/11/360/0).

Endorsing the need for coordination among various sectors and planning approaches for climate change adaptation, the Overseas Development Institute (Mitchell 2011) and others recognize that promoting coordination between any two separate strategies will be difficult for policy makers, and improving institutional and organization coherence among all of them will be very challenging. ODI calls for more research on the politics of policy processes associated with building resilience through multiple strategies at different scales. Energy ministries and power utilities can also incorporate the following measures into their implementation plans:

- Introduce climate change vulnerability and adaptation considerations to criteria used for selecting and prioritizing projects for implementation and financing.
- Develop sector-specific and country-specific screening tools to identify proposed projects at risk.
- Incorporate contingency budgets for specific adaptation interventions as the need arises, including at least order-of-magnitude estimates of the likely costs, risks, and benefits of the adaptation action and inaction.
- Adjust zoning regulations for energy infrastructure (for example, to avoid flood or permafrost zones).
- Design flexible energy infrastructure that can accommodate incremental changes over time.
- Incorporate climate change indicators into energy planning budgeting frameworks.

Many key energy sector policy and planning decisions will be made, at least de facto, by the power utilities, whether government-owned or private. Much of the investment finance will come from the private sector and a substantial amount of new generation is likely to be provided by independent power producers. It is important that private bodies and civil society are involved in discussions and decisions on energy sector governance, planning, policies, and regulations. As a recent dialogue at ADB concluded, energy regulators also have a potentially strong role to play in refining policies, mechanisms, and regulations to improve resilience in an increasingly uncertain environment to better manage possible losses of energy resources or supply and/or to meet higher energy demands (Box 15).

Involving government energy policy makers, economic policy makers, power utilities, regulators, government climate officials, the private sector, and civil society in policy making and planning for more effective adaption to climate change is likely to improve the effectiveness of screening tools, the understanding of the limitations of climate models, and the practicality of local and national guidelines for such issues as choosing locations for new power plants; power plant robustness with regard to storms, floods, and heat waves; stormproofing power plants and T&D systems; and developing more effective renewable energy and energy efficiency programs.

This report has argued that Asia and the Pacific are vulnerable to negative impacts of climate change, and that many of these impacts are expected to be highly significant in the energy sector, substantially increasing costs of electricity or reducing output. In a number of circumstances, the costs of inaction, or poorly considered and executed actions, are expected to be far higher than well-planned and implemented actions to improve energy sector resilience. Better planning and policies, and improved coordination among key ministries, regulators, power producers, and users are essential. As noted in the introduction, inadequate attention to these impacts can increase the long-term costs of energy sector investments, the likelihood that they will not deliver intended benefits, and the probability of failure under climate stress.

This paper has also discussed a wide range of climate variables and their expected impacts on the energy sector. An additional concern, and one reinforcing the need for better coordination and planning efforts, is the added climate change risk of interactions from multiple hazards (Box 16) even when these are not simultaneous. An increase in extreme weather events may expose energy infrastructure to multiple risks requiring adaptation measures well in excess of those that are cost-effective and appropriate for any individual event.

Box 15 Asia–Pacific Energy Policy Makers and Regulators' Statement on Clean Energy and Climate Change

In June 2011, 160 energy policy makers, regulators, government climate change focal points, and private and civil society representatives met at ADB headquarters in Manila to discuss governance, planning, policies, and regulations for "clean energy" (encompassing energy efficiency, renewable energy, and carbon capture and storage). Parts of their joint statement (ADB/USAID 2011), paraphrased below, is applicable to wider energy policy and climate issues:

- The objective of energy policy should be to supply energy services to all at the least full cost to society, which requires understanding energy demand projections. New supply-side investments such as large-scale power plants or transmission lines are often more expensive than improved energy efficiency.
- Environmental externalities, including a carbon price, should be included in all comparisons of energy technology costs.
- Clean energy policy and regulatory decisions are governed and regulated by a complex and overlapping mix of institutions—including energy ministries, renewable energy and energy efficiency departments and agencies, environment ministries, regulators, and the private sector—an institutional mix that complicates decision making and requires extensive coordination to be effective.
- Energy policy makers set broad frameworks whereas "autonomous" regulators have varying levels of discretion, setting policy and developing regulations within their mandates. An "economic" regulator may have a general mandate to provide long-term protection for consumer interests and sustainability, or a more specific mandate to require implementation of energy efficiency or renewable energy measures. Developing and implementing energy policies and good energy regulation is an iterative process involving policy makers and regulators. In some cases, regulators may need specific authority to respond to climate change issues and should be entrusted with this authority.
- Policy makers and regulators need to creatively engage all stakeholders to design effective programs and marshal support for the kinds of programs needed. This includes building the capacity of independent civil society actors and outreach to consumers to ensure a real dialogue on energy governance, and to balance competing interests of government, the public, and investors, among others.
- Policy makers and regulators must develop schemes for measuring performance and reporting on the energy sector. These could include (i) labeling of appliances and equipment, vehicles, and electricity; (ii) energy management systems for businesses and factories (e.g., ISO 50001); (iii) international standards for reporting on the performance of energy efficiency measurement and verification; and (iv) standardized reporting by regulators on national performance outcomes of energy efficiency policies and programs.

Box 16 Risks of Multiple Hazards on Power Sector Infrastructure

Using a consistent measure (maximum lateral deflection), researchers from the U.S. National Institute of Standards and Technology have assessed the combined risks of failure to structures from wind and earthquakes. They warn that a double whammy of seismic and wind hazards can increase the risk of structural damage to infrastructure as much as twice the level implied in building codes, because current codes consider natural hazards individually. This is true even accounting for the fact that such multiple events almost never occur simultaneously.

They explain by analogy. Assume that a motorcycle racer takes a second job as a high-wire performer. “By adding this new occupation, the racer increases his risk of injury, even though the timing and nature of the injuries sustained in a motorcycle accident or in a high-wire mishap may differ. Understandably, an insurer would raise the premium on a personal injury policy to account for the higher level of risk.”

The researchers are continuing to extend their methodology and are proposing modifications to building codes.

Source: Duthinh, D. and E. Simiu. 2010. Safety of Structures in Strong Winds and Earthquakes: Multihazard Considerations. *Journal of Structural Engineering*. 136. pp. 330–333.

Conclusions

There is strong scientific consensus that climate change is happening and that this is mostly due to human activities. A recent assessment of the vulnerability of 193 countries to climate change rated 30 of these countries at extreme risk, of which 9 are ADB DMCs. The assessment excluded most of ADB's Pacific DMCs, many of which are also considered to be at extreme risk. In addition, 5 Asian DMC cities are among only 6 rapidly growing cities globally classified to be at extreme risk, and 5 others are among 10 rated as high risk.

The energy sector is vulnerable to projected changes in climate variables. Increased frequency and intensity of extreme weather events as well as higher temperatures and projected rise in sea level are expected to result in numerous consequences.

Thus, energy in Asia and the Pacific is a vulnerable sector in a vulnerable region.

Energy investment decisions have long lead times and long-lasting effects, as power plants and grids often last for 40 years or more. This explains the need to assess the possible impacts of climate change on such infrastructure, to identify the nature and effects of possible adaptation options, and to assess the technical and economic viability of some (or all) of these options.

This publication aimed to highlight and raise awareness of the exposure and vulnerability of the energy sector to climate change. It also discussed adaptation options available for each source of energy supply as well as for the distribution of energy.

The development of a climate-resilient energy sector would further benefit from the following considerations:

- *Additional and predictable financing* is needed to support approaches that seek to fully integrate adaptation into development planning and processes. Most adaptation financing is now allocated by donors on a project-by-project basis, which forcibly separates adaptation activities from mainstream development work. While separating out funding for adaptation is important for accountability and transparency purposes, it can also add to the challenge of mainstreaming efforts, particularly when adaptation funds and sector budgets are administered independently. Proposals by the Kyoto Protocol Adaptation Fund board[27] to support projects and programs, as well as budget support pilots underway by some donors, will be important models to monitor and assess how these approaches might influence future financing architecture for adaptation. Fully integrating adaptation assessment activities into the project development cycle, such as is

[27] The Kyoto Protocol Adaptation Fund has been established by the parties to the Kyoto Protocol to fund concrete adaptation projects and programs.

proposed in this publication, will often require the project officer to raise additional cofinancing for energy projects.

- *Holistic adaptation solutions are cross-sector.* Sector-based approaches have their limits, and regional ecosystem-based assessments and analyses are needed to influence integrated planning for infrastructure such as energy. Most adaptation responses will require participation across ministries, recognizing that effective coordination will require intense effort. When working with line and sector ministries, support should also be extended to strengthen the ability of often-weaker environment ministries to participate within their given mandates. This strengthens climate change adaptation efforts throughout the whole government rather than single ministries.
- *Adaptation is characterized by decision making under uncertainty.* Uncertainties associated with climate science and socioeconomic trends require a pragmatic, participatory, and flexible approach to constructing scenarios and assessing impacts, vulnerability, and adaptation. Adaptation policies, strategies, and options should thus be more robust with a certain level of flexibility to take advantage of new developments in climate science and technology.
- *Mainstreaming adaptation into the energy sector should take place at the national, sector, and project levels.* Each level has a specific role to play in addressing planning, budgeting, and community-level vulnerability issues. There is value in conducting sector-specific assessments, as each sector will have its own challenges under a climate change lens. There is a need for sector experts themselves to develop practical climate proofing experience.

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Climate Risk and Adaptation in the Electric Power Sector

This report aims to highlight and raise awareness on the exposure and vulnerability of the energy sector to climate change. It also identifies adaptation options available to each source of energy generation as well as for the distribution and end use of electrical energy.

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