Good Practice Note for Energy Sector Adaptation

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Contents

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Executive Summary

Climate change poses direct risks to power sector investments, as the components of this sector are highly sensitive to environmental variables such water availability, extreme weather, and flooding. With this in mind, it is imperative to account for and address these changing conditions during development and design for WB-financed power sector infrastructure. The World Bank has made a commitment to mainstream climate change into its operations[1] and scaling up action for climate adaptation[2]. This good practice note aims to assist World Bank task teams in incorporating climate adaptation and resilience into power sector projects for client countries.

Climate Risks to Power Infrastructure

Overview of Climate Change and Hazards

Global surface temperatures are projected to increase between 0.3°C and 4.8°C by the late 21st century compared to the period between 1986 and 2005, driving a range of global climate hazards. These hazards include:

- **Chronic climate hazards,** which manifest as long-term, gradual changes in conditions, include temperature, precipitation and sea level rise. While both temperature and sea level rise are expected to increase by the end of the century, precipitation levels are projected to fluctuate by region and experience more intense variability.
- **Acute climate hazards**, which manifest as extreme events, include extreme heat, drought, wildfire, extreme precipitation, storm surge and ice events. In the 21st century, the severity and frequency of each of these hazards is expected to increase relative to historical conditions.

Each climate hazard exhibits great deal of regional variability and should be considered within its specific geographic context.

Climate Information for Decision-Making

Both historical and modeled information on climate change are critical when evaluating climate impacts on the power sector.

While climate models provide global projections, some locations, particularly in developing countries, may lack observed historical data. In such cases, climate risk identification and assessment for power sector investments may be compromised, as historical data are integral to identifying current climate-related trends and extremes and for placing future risks in context. To mitigate the consequences of data sparsity, gridded weather station data and model reanalysis products for climate data can help fill in gaps in observational coverage.

Global climate models simulate how climate may change in the future. Models consider different scenarios of future greenhouse gas concentrations to simulate future climate outcomes and project a range of climate outputs (e.g. temperature, precipitation). These simulations can then be coupled to

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[1] WBG (2018). 2025 Targets to Step up Climate Action. http://pubdocs.worldbank.org/en/368601543772742074/2025-Targets-to-Step-Up-Climate-Action.pdf

[2] WBG(2018). Adaptation and Resilience Action Plan. http://pubdocs.worldbank.org/en/189851543772751358/Adaptation-and-Resilience-Action-Plan-Key-Messages.pdf

secondary models that characterize future behavior of other variables (e.g. coastal storms) that can be used as inputs for project feasibility assessments and design studies.

Using climate models effectively requires that task teams understand relevant datasets, associated uncertainties, and the appropriate level of detail needed to answer the problem of interest. Additionally, task teams should be mindful that different climate scenarios and models can provide different outputs, each with their own uncertainties. Using a range of scenarios and multiple models to bracket projection uncertainties and obtain a representative range of potential future climate outcomes will yield projections that more appropriately reflect these uncertainties.

Potential Physical and Performance Related Climate Impacts on the Power Sector

Climate impacts on the power sector are both direct and indirect. Direct impacts represent those that disrupt power supply through component performance and efficiency reductions (e.g. direct damage to infrastructure from extreme weather) and indirect impacts are those that are facilitated by climate hazards (e.g. rising temperatures increase net electricity demand for cooling). These impacts often occur in cascade, leading to compounding downstream impacts for customers and interconnected sectors. For this reason, it is vital that task teams understand the interconnected nature of climate hazards, as well as the sensitivity of relevant assets to compounded or cumulative climate impacts.

Power generation assets are often highly sensitive to direct climate impacts. For example, wind turbines are adversely affected by temperature increases and reduced wind energy, as well as severe weather and flooding. Transmission and Distribution assets, namely substations, powerlines, and towers, are similarly susceptible to direct impacts of climate variability and change.

Climate hazards also introduce a range of indirect impacts across the power sector. For example, hazard events can damage both power infrastructure and transportation routes, limiting power restoration efforts. Hazard events can also increase the demand for power, while at the same time straining or harming necessary power infrastructure. Temporary generation and transmission stoppages can lead to costly indirect impacts that stress downstream infrastructure.

Adaptation Measures for the Power Sector

Measures to help reduce potential climate impacts can address specific climate risks at the project scale, improve system resilience, or can be integrated into power sector planning to increase power system reliability and resilience. Adaptation measures can be organized conceptually into four categories based on the way they seek to manage climate change impacts: protect/harden, retreat/redesign, accommodate/manage, and monitor.

- **Protect/Harden:** Adaptation measures that seek “Protect/Harden” typically employ structural measures to reduce the sensitivity of assets to hazard exposure. Examples of “Protect/Harden” measures include elevating or building a protective wall around coastal assets, undergrounding transmission lines, or installing sectionalizing switches in primary and secondary distribution feeders.
- **Retreat/Redesign**: “Retreat/Redesign” adaptation measures, which site assets out of hazardous locations, are adopted when it is not feasible or effective to rely on incremental measures in the face of continuous change. Examples of “Retreat/Redesign” measures include selecting a high-

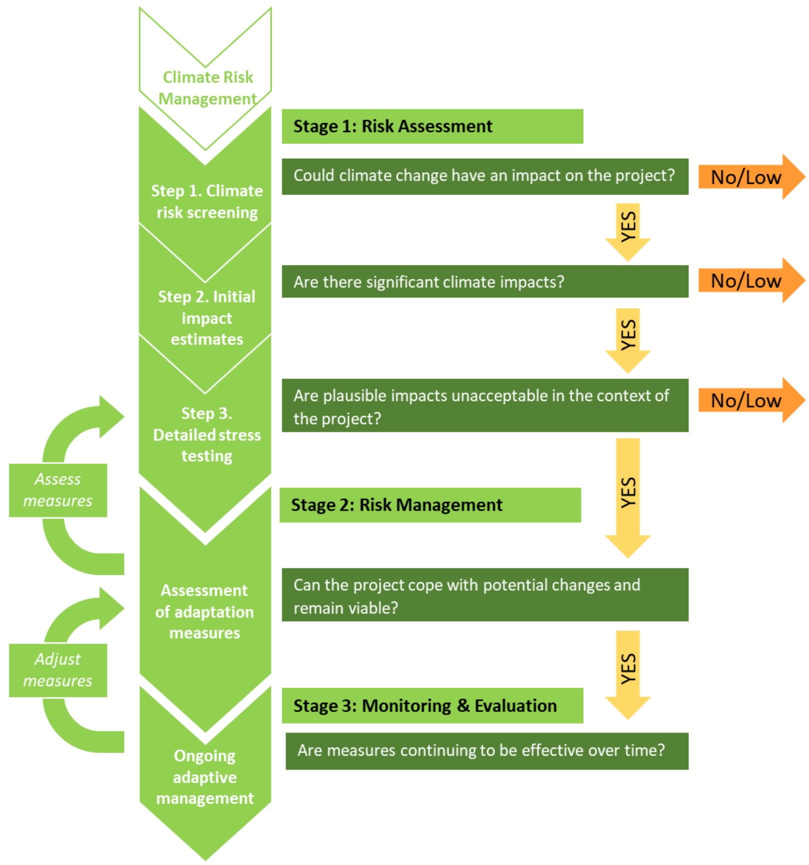
elevation site for new power-plant construction, designing alternate transmission routes to avoid wildfire zones, or moving coastal substations inland.

- **Accommodate/Manage:** "Accommodate/Manage" adaptation strategies account for – rather than resist – impacts of climate change during operation and design processes. These measures integrate knowledge of hazard zones into planning protocols and asset configuration, allowing assets and activities to effectively accommodate future conditions. Examples of "Accommodate/Manage" measures include purchasing pumps and implementing water removal protocols in flood zones or implementing consumer demand reduction programs to reduce peak load during extreme heat.
- **Monitor:** Monitoring climate risks and the effectiveness of adaptation measures can improve real-time system operations and enhance understanding of evolving risks. In turn, task teams can better position themselves to inform design and adjustment of future adaptation measures. Examples of "Monitor" measures include securing access to local tide gauge information to track long-term water level change, observing changes in annual high temperatures and peak load, and conducting remote monitoring of distribution transformer load and temperature.
- **Policy, Planning, and Capacity-Building:** Some of the most important climate adaptation measures are those that take the form of policy, planning, and institutional changes. Measures at this level increase the long-term ability of relevant in-country government and energy-sector actors to systematically account for impacts and risks associated with climate change in energy sector planning. Measures in this category may include revision of nationwide standards for infrastructure design, mainstreaming of climate data and resilience expertise and considerations in energy planning processes, stakeholder engagement processes around energy sector resilience, and investment in data collection and analysis (e.g. hydromet services) specifically relevant for the energy sector.

Incorporating Climate Risk Management into Project Design

The following process for climate risk assessment and management is based on a hierarchical model, which progresses from a broad-based, all-encompassing screening approach to a narrow, more detailed assessment of the most concerning hazards. Figure ES-1 depicts the progression of climate risk assessment and management across the project cycle. Ideally, the climate risk management process should proceed in alignment with the project cycle, as well as with the co-benefits assessment process.

Figure ES-1. Progression of Climate Risk Management and Key Questions for each sub-Stage



The precise alignment of climate risk assessment with the project cycle will differ from project to project, as not all World Bank projects follow the same progression. Additionally, the diversity of project types, adaptation types, and specific contexts means that there is not a single one-size-fits all methodology for climate adaptation. When selecting assessment approaches, task teams should consider the cost/complexity of analysis, magnitude of risk, cost of adaptation measures, timeline, and data availability.

Stage 1: Climate Risk Assessment

Climate risk assessment should encompass the exposure, sensitivity and adaptive capacity of the power sector. The first step of the assessment is a qualitative evaluation of whether climate change is a risk to a project and a projection of how this risk may manifest. The Climate and Disaster Risk Screening Tool, which provides a sector-specific structure for qualitative risk assessment, is one of several tools that can be used to guide project teams in this process. After the screening process, project teams should generate quantitative estimates of potential impacts associated with high-risk climate change variables, with the goal of assessing these variables at an order of magnitude. If this analysis uncovers climate risks of a potentially significant magnitude, these risks should be assessed at a fine level of detail to determine whether they are unacceptable in the context of the project. In many cases this analysis will be highly complex and will likely require a collaborative approach among experts.

Stage 2: Climate Risk Management: Assessment of Adaptation Measures

Based on the results of the climate risk assessment process, project task teams and asset managers should develop a strategy for reducing climate risks to a level that is acceptable based on project performance metrics. Determination of an "acceptable" level of risk is context-specific, as thresholds for damaging conditions may vary widely across different asset types. Once thresholds are established, adaptation measures can be evaluated and selected. There are a wide array of factors to consider in selecting adaptation measures, including cost, anticipated damages avoided, robustness, flexibility, and co-benefits. While there is no universal methodology for evaluating potential adaptation measures, useful tools include cost-benefit analyses, multi-criteria analyses, and scenario analyses—though each comes with benefits and limitations.

Stage 3: Ongoing Adaptive Management, Monitoring and Evaluation

Ongoing adaptive management, monitoring, and evaluation should occur throughout the life of the project. Specifically, resilience plans should allow investments to respond adaptively to newly emerging conditions, growing information, and changing societal trends. To facilitate this, task teams are recommended to monitor environmental and technological change, as well as asset performance. Task teams may consider the use of adaptive management strategies such as the flexible adaptation pathways framework, which provides a thresholds-based framework for low-regrets adaptation in the face of uncertainty.

Assessing Climate Adaptation Co-Benefits in the World Bank Framework

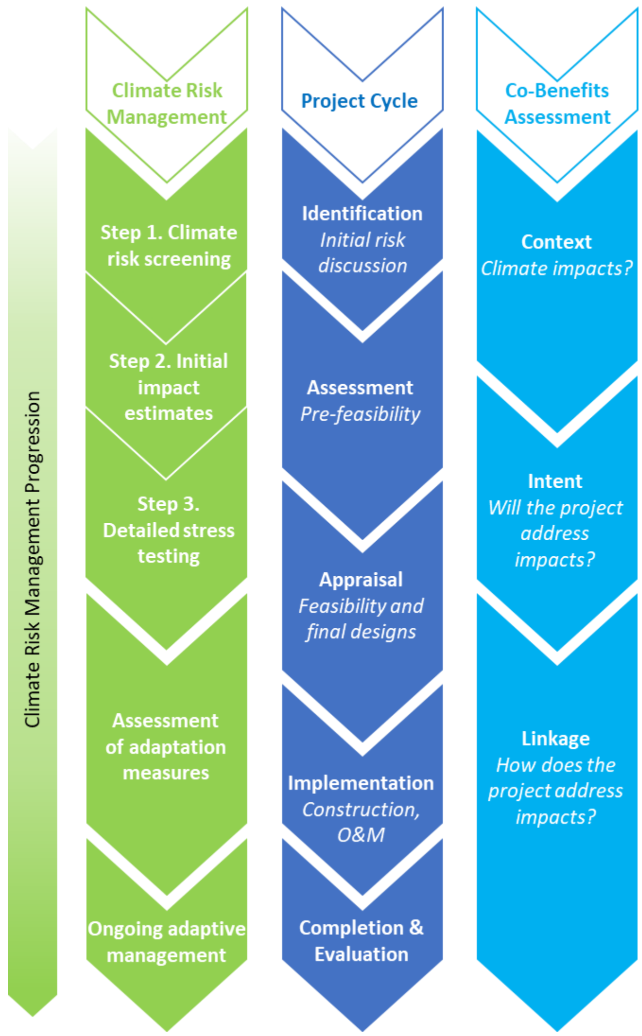
The World Bank has set a goal for 28 percent of its investments to be climate-related by 2020, with a new set of climate targets for 2021-2025, doubling its current 5-year investments to around $200 billion in support for countries to take ambitious climate action. The new plan significantly boosts support for adaptation and resilience, recognizing mounting climate change impacts, especially in the world's poorest countries. All projects should be assessed to determine whether they deliver adaptation or mitigation co-benefits under the joint Multilateral Development Bank (MDB) co-benefits methodology. As per the methodology, task teams are required to describe how the incumbent project design has considered climate change impacts and adaptation. This requires task teams to include information on: (i) local climate change **context** for the project, (ii) explicit **intent** of the project design to address climate change risks, and (iii) how the project activities **link** to identified climate change vulnerabilities.

Adaptation co-benefits are counted based on the incremental cost of measures that directly address climate change impacts. As such, for many projects, climate adaptation co-benefits will reflect only a portion of project costs. For example, if a project team determines that future projections for extreme heat require higher-capacity transformers than historical temperatures would warrant, only the incremental cost of those higher-capacity transformers should be counted as a climate change co-benefit, rather than the entire cost of the transformers. That said, other projects may have their entire costs counted as climate adaptation co-benefits. For example, if a project has been designed specifically to rehabilitate and strengthen the transmission and distribution system in response to stronger and more frequent hurricanes. With this in mind, project teams should clearly state which specific project components and sub-components were partially or fully intended to address climate change impacts, and should fully document and justify their best estimates of the incremental costs associated with these measures.

Introduction

Climate change poses direct risks to power sector investments given the sensitivity of power system component performance to changes in water availability, extreme weather, and flooding. In some cases, these risks may be exacerbated by heavier burdens placed on power systems from a higher demand for cooling from residential,[3] industry, and other key sectors owing to rising temperatures. Globally, climate change is manifesting through higher temperatures, changes in precipitation patterns, increasing intensity of storms, and rising sea levels. Given the long-life spans of power infrastructure (15-40 years for power plants and 40-75 years for transmission lines) and the expected changes in cooling and heating demands, it is imperative to account for and address these changing conditions during project development and design.

Figure I-1: Progression of Climate Risk Management and Co-Benefits Assessment over the Project Cycle



World Bank's commitment to mainstream climate change into its operations include: (i) greenhouse gas accounting; (ii) climate risk screening; (iii)assessment of climate co-benefits; and (iv) integrating shadow price of carbon in project economic analysis for all IDA/IBRD operations. Climate risk management, specifically the assessment of climate change risks and measures to increase project resilience, is evolving as part of routine project due diligence at the World Bank. The World Bank tracks financial resources that it invests in activities that provide "climate co-benefits," requiring all projects to assess adaptation (and mitigation) co-benefits of projects.

Ideally, the stages of risk management and co-benefits assessment would be ongoing as the project evolves from identification to completion and evaluation, as illustrated in Figure I-1.[4] In this figure, the green flow chart lists the various steps involved in identifying climate change risks for a project and developing appropriate adaptation/resilience measures to address those risks. These steps are shown in parallel to the dark blue flowchart that presents the key stages in the project cycle to indicate at approximately what stage climate risks should be identified and addressed. Recognizing that project

[3] Especially in areas where GDP is rising, and penetration of cooling systems is increasing.
[4] **Error! Reference source not found.** reflects the steps in the World Bank Project Cycle, with the exception of N egotiations & Board approval.

progressions differ, the alignment of these three processes with each other is intended as an rough and illustrative guide rather than a strict prescription.

At the right hand side of **Error! Reference source not found.**-1, the light blue flow chart includes the t hree-step approach for assessing climate adaptation co-benefits of WB projects that follow the Joint MDB methodology for tracking climate finance.[5] The parallel presentation of the flowcharts is intended to show at what stage in project cycle and climate risk management teams can capture the information required for assessment of climate adaptation co-benefits. Conducting the climate risk management process with co-benefits tracking in mind can streamline the process of evaluating co-benefits and increase the likelihood that co-benenfits are attributed to a project. Task teams can use the process of tiered risk assessment and adaptation measure selection to establish the climate adaptation context, intent, and linkage of the project, and should make an effort to track best-estimates of incremental adaptation costs throughout the process.

Finally, power sector performance and reliability can also be addressed further upstream in power system planning. Traditional integrated resources planning can incorporate and assess the impact of climate risks on different investment portfolio strategies to determine which portfolios perform best under different risk scenarios. This type of assessment can inform power system master plans by identifying performance trade-offs of different investment strategies, including the incremental costs of adaptation, greenhouse gas emissions, reliability, and other key metrics.

Good Practice Note: Purpose and Structure

The purpose of this Good Practice Note is to assist World Bank task teams in incorporating climate resilience into energy projects for client countries. This will minimize future infrastructure damages and recovery costs due to climate change impacts and improve the outcome and service delivery of World Bank investments. This document covers investment lending and policy loans for the following power sector components – generation (solar, offshore/onshore wind, geothermal, gas, biogas), transmission, and distribution.[6] While information is targeted at these investment types, the climate risk assessment and management process outlined in this note may also be applied more broadly to energy sector investments.

The Good Practice Note includes four sections that provide an overview of climate hazards and impacts, adaptation measures, risk management approaches, and co-benefits assessment. In addition, there are five appendices that provide more detail and background on these topics, including four case studies, and a set of “where to find it” resources for task teams looking for more information.

The Good Practice Note is structured as follows:

- **Section 1: Climate Risks to Power Infrastructure:** This section provides a high-level overview of chronic and acute climate hazards and their projected changes (at a global scale), as well as information on how to use climate information in decision-making, and information on the potential climate change risks to power sector assets, with specific mechanisms of impact as a

[5] The World Bank. 2019. MDB Climate Finance Hit Record High of $43.1 Billion in 2018. Press Release No: 2019/202/CCG.

[6] Including investments in grid extension as part of increasing energy access.

result of hazards (e.g., extreme heat impacts on large power transformers, transfer capability and derating/degradation of thermal generation capacity).

- **Section 2: Adaptation Measures for the Power Sector**: This section provides a high level overview of adaptation measures that can be incorporated into project design to address potential climate impacts. These measures are organized conceptually into five categories that describe the approach to addressing climate change impacts: (1) protect/harden; (2) retreat/redesign; (3) accommodate/manage; (4) monitor; and (5) policy, planning, and capacity-building. A variety of different types of measures are described, including structural, policy and planning, land use, and operational.
- **Section 3: Incorporating Climate Risk Management into Project Design:** This section describes the progressive stages of climate risk management throughout the project cycle, including risk identification, assessment, and mitigation. The section outlines different types of analytical approaches and methods that can be applied.
- **Section 4: Assessing Climate Adaptation Co-Benefits:** This section describes the World Bank Framework on assessing climate adaptation co-benefits as part of project due diligence.

Detailed information is provided in the five Annexes, including:

- **Annex 1: Case Studies**. This Annex includes 4-5 case studies that illustrate the application and progression of climate risk assessment and management methods, and the relationship of the outcomes of these approaches to the development of the co-benefits context, intent, and linkage.
- **Annex 2: Climate Data and Resources.** This Annex lists resources related to climate data, including information on climate change models, climate indices relevant to assessing potential power sector risks, and resources for gathering information on historical climate and future climate projections.
- **Annex 3: Resources for Climate Impacts to Power Sector Components.** This Annex provides a set of resources to explore for further information on climate risks to power sector components.
- **Annex 4: Details on Adaptation Measures.** This Annex contains a suite of adaptation measures that address specific climate hazards and impacts to power generation, transmission, and distribution assets. The tables adaptation measures by asset, type of impact(s) and climate hazard(s) addressed, type of measure (e.g., structural, policy, land use, or operational), and cost range (where available).
- **Annex 5: Climate Change Adaptation Funds.** This Annex includes a list of multilateral and bilateral climate change adaptation funds.
- **Annex 6: Climate Risk Management Methods and Tools.** This Annex includes analytical tools and resources that can be used to assess climate risk, and evaluate adaptation measures.

Task teams can choose to read through the Good Practice Note Sections sequentially given the logical presentation of information; or, task teams can refer to specific Good Practice Note Sections and Annexes to address specific topics as they arise in project preparation.

Section 1. Climate Risks to Power Infrastructure

Understanding climate trends and risks is important as they individually and collectively impact key assets in the power sector. In the most recent global climate change assessment, the Intergovernmental Panel on Climate Change (IPCC) concluded that it is extremely likely that a build-up of anthropogenic greenhouse gases (GHGs) in the atmosphere is the dominant driver of global warming since the start of the industrial period.[7] Observed trends over the 20th century reveal that most land areas have very likely experienced warmer and fewer cold days and nights and more frequent hot days and nights.[5,8] More recently, the last decade was the warmest on record, with temperatures increasing globally at an accelerating rate since 1970.[8]

Increased atmospheric warming drives a range of global climate hazards and changes. These climate hazards include both chronic events, such as long-term sea level rise and changes in annual precipitation and seasonality, as well as acute events, such as heatwaves, droughts and wildfires. In turn, climate hazards can result in both direct and indirect impacts to the power sector. Potential impacts depend on infrastructure location (i.e., level of exposure), type and condition (i.e., level of sensitivity), and the frequency and intensity of the climate hazard. For example, sea level rise and storm surge most likely impact power assets and services in low-lying coastal regions, while drought and wildfires are more likely to impact power assets located in arid and forested regions, respectively. Similarly, gas, geothermal and hydropower generation are more vulnerable to water shortages compared to wind and solar generation, while older assets are generally more sensitive than new or retrofitted assets.

This section provides a high-level overview of both chronic and acute climate hazards and their projected changes in a warming world, including temperature profile, annual and interannual precipitation and variability, sea level rise, extreme heat, icing and cold snaps, drought, wildfires, extreme precipitation and flooding, and coastal storms. The description of climate hazards is followed by a section focused on best practices in the use of climate information for decision making. Finally, climate hazards are discussed in terms of their potential physical and performance related impacts on the power sector. Ultimately, the specific characteristics of climate change vary by location; therefore, stakeholders and investors need to be aware of both trends and future projected climate changes as they apply to their specific local and regional context.

1.1. Overview of Climate Change and Hazards

Global climate projections reveal a future defined by increasing exposure to a range of climate changes and hazards. Global surface temperatures are projected to increase between 0.3°C and 4.8°C by the late 21st century compared to the period between 1986 and 2005, increasing both daily maximum and nighttime minimum temperatures.[7] In turn, increasing temperatures are projected to drive many associated chronic climate changes. For example, seasonal and year-to-year precipitation variability, as well as the contrast in mean precipitation between wet and dry regions, is expected to increase in a

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[7] IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[8] GCRP. 2017. Climate Science Special Report: Fourth National Climate Assessment. U.S. Global Change Research Program. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (Eds.)]. U.S. Government Printing Office: Washington, D.C. 477 pp. doi:10.7930/J0J964J6.

warming climate.[9] At the same time, warmer temperatures are expected to increase ice loss from large ice sheets and invigorate ocean thermal expansion, causing an acceleration of global sea level rise.[7,10]

In many cases, long-term chronic climate changes increase the likelihood of acute, lower probability climate hazards. According to the IPCC, it is virtually certain that extreme heat days will become more frequent and very likely that heatwave frequency and duration will increase through the 21st century.[7] Drought severity and wildfire risk are expected to increase relative to historical conditions due to increasing extreme heat and changing precipitation patterns.[8] Finally, warmer air and ocean temperatures drive increases in extreme precipitation, intensity of coastal storms, storm surge, and wind, as well as alter the impact of winter precipitation, including icing events. Ultimately, climate changes will not be uniform globally, but instead reveal a great deal of regional variability. For example, the Arctic is warming at nearly twice the rate of the global average. As a result, actors should be mindful of climate trends and projections within a regional and local context as they determine future actions.

Table 1-1 provides a summary of both chronic and acute climate hazards that impact the power sector. More detailed information on climate projections is provided in Annex 2.

Table 1-1: Summary and Projected Changes of Climate Hazards Impacting Power Sector

Climate Hazard	Projected Change	Type
Temperature	Global surface temperatures will likely increase between 0.3°C and 4.7°C by the late 21st century relative to the period between 1986 and 2005. Increases in temperature profiles (both daily maximum and minimum temperature).	Chronic
Precipitation	Regional increases and decreases in average precipitation. Increase in seasonal and year-to-year precipitation variability and extremes.	Chronic
Sea Level Rise	Very high confidence that global mean sea level will rise 0.2 to 2.7 meters by end of century.	Chronic
Extreme Heat	Extreme heat days and heat wave frequency, magnitude and duration will increase through the 21st century.	Acute
Drought	Drought severity is expected to increase relative to historical conditions, particularly in historically arid regions.	Acute
Wildfire	Wildfire frequency and severity is expected to increase, particularly in areas already susceptible to wildfires.	Acute
Extreme Precipitation/Riverine Flooding	The frequency and intensity of extreme precipitation will likely increase over the 21st century over many areas of the globe, which increases the risk of riverine flooding.	Acute
Coastal Storms/Storm Surge/Winds	Storm intensity, winds, and rainfall rates will likely increase over the 21st century. Stronger storm surge coupled with expected sea level rise will exacerbate coastal flooding and inundation.	Acute

[9] IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)]. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
[10] Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas. 2017. Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services. Silver Spring, MD.

Climate Hazard	Projected Change	Type
Icing and Cold Weather Outbreaks	General warming decreases fraction of precipitation forming ice, but heavy precipitation increases may intensify individual icing events.	Acute

1.2. Climate Information for Decision-making

Information on climate variability and change are critical inputs to evaluate climate impacts on the power sector. Climate information can be broadly categorized as either historical data or future projections. Ultimately, both perspectives (i.e., past and future) are necessary to make climate-informed decisions regarding power sector impacts in a warming world. Critical to evaluating impacts is that climate information is accessible, and useful (i.e., can be tailored to the specific problem).[11] Unfortunately, data sparsity can compromise risk identification and assessment in some of the most climate vulnerable locations in the world, particularly in developing countries. While climate models provide projections globally, some regions may lack historical data because of limited spatial coverage of observing stations, instrumental issues, or lack of technological resources.[12] Annex 2 provides details and tables on available climate resources for both historical data and future projections, relevant indices, and how they can be used to evaluate climate impacts on the power sector.

Historical data are relevant to decision making because they help identify current climate related risks and, in turn, place future risks into context. Historical data also provides important insights into climate trends and extremes and can characterize how a particular location may be sensitive to future climate variations. Historical data is often drawn from weather stations, gridded weather station data, satellite-derived products, model reanalysis, and indigenous knowledge. While observed data offers the truest measurement of a particular climate variable at a particular location over time, the absence of this information is a characteristic of data sparse areas. In fact, gridded data, reanalysis products, amongst others, were developed specifically to help fill in gaps in observational coverage.

In contrast, global climate models simulate how climate may change in the future. Models (such as the latest generation Coupled Model Intercomparison Project (CMIP)-5 models, see Annex 2 for more details) consider different scenarios of future greenhouse gas concentrations (e.g., low, medium and high) to simulate a range of future climate outcomes and project a range of climate outputs, including temperature, precipitation, wind and other physical parameters. These simulations can then be coupled to secondary models that characterize future behavior of other variables, including sea level rise and coastal storms. While global climate models produce information at roughly 100 km resolution , downscaling techniques can generate climate simulations at resolutions as fine as 1-2 km. These finer resolutions may be useful in some cases, but in other cases may prove unnecessary for adequate assessment of risk Climate models are developed and maintained by research groups around the world and simulations are made available through online resources outlined in Annex 2.

[11] Dinku, T, K. Asefa, K. Hilemariam, D. Grimes, and S. Connor. 2011. Improving availability, access and use of climate information. WMO Bulletin 60 (2).
[12] Dinku, T., and M. Hellmuth. 2013. Informing Climate-resilient development in data sparse regions. USAID Working Paper.

Using historical or projected climate information requires some understanding of underlying datasets, associated uncertainties and the appropriate level of detail needed to answer the problem of interest.[13] For example, appropriate analysis of historical hazard information, existing assessments, and literature indicating magnitude and direction of projected change may provide the level of information needed for decision making (e.g., risk screening, impact identification) at a lower cost than formulating a new assessment. Similarly, if the expected impacts of a project will be a decade or less, it may be sufficient to look at historical climate variability to understand short-term risks.

Finally, several considerations should be made to effectively use climate models if they are needed, e.g. timeframe of interest, range of mode outputs and associated uncertainty. For example, thirty year observation time periods are often used to represent average climate conditions in the future. At the same time, actors should be mindful that different climate scenarios and models can provide different outputs, each with their own uncertainties. Recognizing and accounting for the sources of uncertainty in climate information is important. Three key sources of uncertainty are: 1) natural climate variability; 2) limitations of the models used to represent the climate system; and 3) uncertainty around future emissions—future emissions scenarios are used to generate climate projections.

While uncertainties do not equate with a lack of information, nor should they act as a barrier to action, best practice suggests that when using climate projections, it is important to use a range of scenarios and multiple models to bracket projection uncertainties and obtain a representative range of potential future outcomes. This approach also enables a more careful analysis of plausible low-probability, high-impact scenarios. In contrast, using single, best-guess estimates of future conditions fails to consider the range of potential future climate outcomes, as well as model uncertainties, and can potentially lead to poor preparation, design and investments.

1.3. Potential Physical and Performance Related Climate Impacts on the Power Sector

Power sector assets and services are vulnerable to both chronic and acute climate hazards, which impact power generation (e.g., derating/degradation of thermal generation performance), transmission and distribution (e.g., transfer capability), as well as power demand. In turn, climate impacts on the power sector are both direct and indirect. Direct impacts represent those that disrupt power supply through component performance and efficiency reductions, such as direct damage to infrastructure from extreme weather, or solar, wind and distribution efficiency losses from temperature increases. In contrast, indirect impacts are those that are facilitated by climate hazards. For example, rising temperatures increase net electricity demand for cooling.

Because the power sector is highly interconnected with other critical sectors, including emergency services, communication services, and health care facilities, power outages from climate hazards can lead to a range of additional adverse indirect impacts to systems downstream of the power sector.[14] Oftentimes, direct and indirect impacts occur in a cascade, leading to compounding consequences for communities that the impacted power sector serves.

Table 1-2 through Table 1-4 highlight relevant direct impacts on asset types within the power sector, including power generation, transmission and distribution. These tables are followed by a discussion of

[13] USAID. Primer: Using climate information for climate risk assessment
[14] U.S. DOE. 2016.

indirect climate impacts related to all asset types, and the interconnected consequences that can emerge from a disrupted power sector.

Table 1-2: Direct Climate Impacts on Power Generation Assets

Generation Asset	Direct Climate Impacts
Solar	- Temperature increases lower solar power cell efficiency and energy output (0.4% reduction per 1°C)[15] - Drought and extreme heat and wind causing atmospheric dust pollution lowers solar power energy output (up to 20% reduction due to dust cover on solar panels) and increases risk of panel hotspots limiting panel performance - Increased precipitation and humidity lead to panel delamination - Storms physically damage solar panels and reduce panel lifespan from debris, wind and lightning[16] - Storms physically damage floating solar installations, particularly near coastal locations - Flooding causes water damage and erosion of generation infrastructure - Temperature increases reduce battery efficiency and lifespan (up to 50% battery lifespan reduction per 8°C) - Droughts reduce supply of cooling water and steam generation for concentrated solar power systems - Extended cloudiness can cause low current events and outages
Wind	- Temperature increases lower wind power generation (0.33% per 1°C) - Reduced wind energy could decrease wind power generation regionally[17] - Strong coastal storms can permanently damage offshore wind turbines (model simulations estimate up to 50% of turbines are destroyed within 20 years in most vulnerable offshore locations)[18] - Severe weather and winds threaten onshore wind turbines - Coastal storms and flooding causes salt water corrosion of electrical components - Riverine flooding causes water damage and erosion of generation infrastructure
Geothermal	- Droughts and shift in precipitation patterns reduces reliability of power plants due to insufficient supply of cooling water - Warmer cooling water intake temperatures reduce thermal gradient and decreases generation efficiency
Gas	- Increasing temperatures reduce natural gas-fired combustion turbine output - Drought conditions lower water available for cooling during power generation

[15] Performance decreases as linked to capacity reductions presented in this chapter are relative to reference temperatures, which may vary across different types of equipment.

[16] Zaini, N., et al. 2017. Lightning surge analysis on a large scale grid-connected solar photovoltaic system. Energies, 10(12), 2149.

[17] Karnauskas, K.B., J.K. Lundquist, and L. Zhang. 2017. Southward shift of global wind energy resource under high carbon dioxide emissions. Nature Geoscience 11:38-43.

[18] Rose, S., P. Jaramillo, M. Small, I. Grossmann, and J. Apt. 2012. Quantifying the hurricane risk to offshore wind turbines. Proceedings of the National Academy of Sciences of the United States of America.

Generation Asset	Direct Climate Impacts
	- Storms and flooding can damage power generation facilities; particularly vulnerable are intake structures that draw cooling water from rivers
Hydropower	- Temperature increases intensify reservoir and watershed evapotranspiration and reduces water available for power generation - Precipitation changes create shifts in peak flow and peak generation - Extreme precipitation increases sediment concentration in reservoir water and heightens flood risk management responsibility

Table 1-3: Direct Climate Impacts on Power Transmission Assets

Transmission Asset	Direct Climate Impacts
Substations	- Temperature increases reduce substation capacity (up to 2%-4% per 5°C)[11] and accelerate transformer aging - Flooding causes direct damage to substations, including loss of HVAC systems, control rooms and communication systems, and foundational erosion
Transmission Lines/Towers	- Temperature increases reduce transmission line efficiency - Warmer nighttime temperatures and lower wind speeds amplify efficiency reductions - Temperature increases cause overhead transmission line sag, increasing risk of contact with surrounding vegetation and the risk of fire ignitions - Increased precipitation causes faster growth rates of vegetation, compounding risk of overhead transmission line contact - Storms impact transmission lines and towers through wind and debris damage - Wildfires can cause physical damage to transmission line infrastructure; wildfire heat and soot can reduce capacity - Riverine flooding can directly damage infrastructure and scour/erode transmission tower foundations - Ice accretion can cause transmission line degradation, malfunction and low performance

Table 1-4: Direct Climate Impacts on Power Distribution Assets

Distribution Asset	Direct Climate Impacts
Substations	- Temperature increases reduce substation capacity (up to 2%-4% per 5°C)[11] - Flooding causes water damage to substations and underground cables
Distribution Transformers	- Temperature and load demand increases accelerate transformer aging and reduce capacity
Distribution Lines/Poles	- Temperature increases reduce distribution line efficiency (0.5%-1% per 1°C) - Warmer nighttime temperatures and lower wind speeds amplify efficiency reductions - Temperature increases cause overhead distribution line sag, increasing the risk of short-circuiting if in contact with surrounding vegetation - Increased precipitation causes faster growth rates of vegetation, compounding risk of overhead distribution line contact

Distribution Asset	Direct Climate Impacts
	- Storms compromise distribution lines through tree-on-line damage - Wildfires cause physical damage to distribution lines and poles - Riverine flooding can directly damage infrastructure and scour/erode distribution pole bases - Sea level rise and coastal flooding damages distribution infrastructure and increases salt water exposure and corrosion of electrical components, particularly for buried lines - Ice accretion can lead to distribution line degradation, malfunction and low performance - Heavy snow events increase the risk of tree-on-line events

Indirect Impacts on the Power Sector

Climate hazards also introduce a range of indirect impacts across the power sector. Indirect impacts are secondary impacts that are facilitated and made more likely by climate hazards. Power infrastructure in low-lying coastal countries are particularly vulnerable to storm surge and erosion from coastal storms, which are projected to intensify with climate change. At the same time, coastal inundation can cause temporary damage to transportation routes, impeding access to facilities for restoration and potentially prolonging outages. For example, Belize could experience a more than 40% increase in the extent of storm surge inundation, which will increase exposure and vulnerability across critical components of the power sector there through both direct and indirect impacts.[19,20]

Regional electricity consumption is closely related to temperature. As a result, projected temperature increases are expected to increase the net demand for electricity, facilitating indirect impacts across the power sector such as accelerated transformer aging and overloading. Transmission lines transporting energy from generators to end users can be particularly sensitive to heatwaves (both due to direct impact of extreme heat on transmission lines thus reducing their capacity and due to indirect impact of increased electricity demand during heatwave can put a strain on these transmission lines), which can contribute to power disruptions or outages. For example, a 2012 heatwave in India contributed to transmission failures that caused two consecutive catastrophic power outages affecting more than 620 million people.[21]

Alternatively, climate hazards can initiate temporary generation and transmission stoppages that lead to costly indirect impacts. For example, winds associated with storms exceeding cut-out speeds can initiate turbine shutdowns and cause sudden power losses to the entire system. Additionally, utilities may voluntarily shutdown high voltage transmission lines in wildfire prone areas during times of excessive wind, heat and drought. While these actions smartly aim to avert wildfire ignitions from transmission infrastructure, power shutdowns stress downstream infrastructure, including emergency services and critical community utilities.

[19] Dasgupta, S., et al. 2009. Sea-level Rise and Storm Surges: a comparative Analysis of Impacts. World Bank.
[20] Acclimatize, 2016. Building Climate Resilience in Belize's Energy Sector.
[21] Anel, J., et al. 2017. Impact of Cold Waves and Heat Waves on the Energy Production Sector. Atmosphere 8(11).

Indirect climate impacts can be particularly disruptive to electricity transmission and distribution. In particular, wildfires present a range of indirect impacts. Most importantly, wildfires caused by transmission line ignitions during wind storms or drought conditions can manifest severe consequences for impacted communities and ecosystems at both local and regional scales. In turn, fire retardants used to combat wildfires can damage and foul transmission lines. Warmer and wetter climates increase vegetation growth in some regions, potentially triggering more frequent tree-on-line events, power disruptions, and outages, as well as increasing wildfire fuel and risk.

Finally, protracted droughts can decrease water levels in rivers and ports and disrupt shipping routes and barge deliveries, causing fuel transportation delays.[22] Droughts can also inhibit water resources in other areas, including groundwater extraction, which limits cooling water supply for power generation. This problem is particularly acute in countries that experience water shortages and where groundwater aquifers are already small, such as Caribbean island nations.[23]

Cascading Impacts on the Power Sector

The climate hazards and impacts discussed in this section are unlikely to occur individually, but rather in parallel, which can result in compounding impacts on the power sector. For example, extreme heat events may coincide with drought conditions, leading to compounding power generation and transmission reductions from both temperature stresses and reduced water resources. Extreme heat can also increase demand for electricity. In addition, climate hazards can increase the likelihood of subsequent hazards, creating a cascading effect that amplifies the risk of compounding impacts. For example, droughts and water shortages precondition wildfires through landscape desiccation and by increasing available fire fuels. Ultimately, the interconnected nature of climate hazards and sensitivity to compounding impacts across power sector assets must be better understood to address overall impacts on the power sector. Similarly, while capacity decreases due to rising temperatures are relatively small for individual assets, the cumulative impact on the system performancecould be substantial in the absence of demand reductions or increased power supply.[22]

Other Power System Risks

Climate hazards impact other areas of the power sector, including production, generation and transport of other fuels including, natural gas, coal and petroleum products. For example, increased water stress due to more severe droughts, increased water demand, and groundwater extraction could decrease water availability for cooling and, in turn, generation capacity at thermal power plants.[22] Furthermore, transportation of energy products are vulnerable to a range of climate and natural hazards. For example, coal is often transported to power plants along rail lines, which frequently follow low-lying coastal areas and rivers connecting material hubs. Many rail systems have been increasingly inundated and compromised by extreme precipitation, riverine flooding, and storm surge, resulting in delivery disruptions and temporary interruptions of electricity generation at power plants.[22] Similarly, landslides and (non-climate related) earthquakes can damage gas pipelines, potentially leading to rupture, leakage and ignitions.

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[22] DOE. 2013. U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather.

[23] NREL. 2011. Energy Policy and Sector Analysis in the Caribbean (2010-2011).

Strengthening coastal storms and surge can also lead to direct physical damage to heavy fuel oil storage infrastructure. As a result, prolonged disruptions to fuel production, storage, and transportation due to extreme weather, such as the impact Typhoon Mangkhut had on petrochemical ports in southeast China in 2018, can have significant indirect consequences for downstream services and industries.

Section 2. Adaptation Measures for the Power Sector

There are a wide range of adaptation measures that can help to reduce potential climate impacts. These measures can address specific climate risks at the project scale, improve system resilience, or be integrated into power sector planning to increase power system reliability and resilience. Adaptation measures can be organized conceptually into four categories based on the way they seek to manage climate change impacts: protect/harden, retreat/redesign, accommodate/manage, and monitor.[24] Adaptation measures include structural measures (e.g., elevating substations) and non-structural measures (e.g., policy measures, regulations, operational changes, demand-side management). Frequently, a combination of mutually reinforcing adaptation strategies—combined in a portfolio approach—is most effective.

Annex 4 contains a compendium of adaptation measures for assets in the power sector. These measures are sorted by asset type, and are presented with approximate cost estimates where available. This list of measures should serve as a starting point for considering what type of measures may be available and appropriate for particular assets. It is not intended as a substitute for careful engineering analysis, or for site-specific expert guidance where risks are severe.

2.1. Protect/Harden

Adaptation measures that seek "Protect/Harden" typically employ structural measures (including changes in land use and green infrastructure, and engineered solutions) to reduce the sensitivity of assets to hazard exposure.

Structural adaptation measures that protect or harden against impacts on asset functionality involve changes to asset and system engineering that can be applied throughout the power system. Structural measures can be designed to reduce the probability of damage or disruption through incremental change to hardening of existing or planned assets. For example, at a substation in a coastal location that may be exposed to an increase in frequency or magnitude of flooding due to sea level rise, assets can be elevated or protected with physical barriers (including green infrastructure) to a design standard that accounts for some amount of the projected sea level rise (e.g., 1 meter). Such physical measures provide an incremental amount of adaptation, which can be monitored against the changing conditions and applied in greater increments as needed. Other examples of measures that protect and harden are listed in Table 2-1.

[24] Based on USAID, "Energy Systems: Addressing the Impacts of Climate Change on Infrastructure," 2012.

Table 2-1: Example protection/hardening adaptation measures

Protect/Harden			
Hazard	Asset Type	Example of Measure	Associated Cost (Where estimates are available)
Coastal storms	*Generation –* Offshore wind	Construct towers using monopile or twisted jacket foundation[25]	Average costs of twisted jacket foundations are often not readily available. However, twisted jacket foundations often reduce the total foundation cost in terms of initial capital investment and maintenance costs[26]
Wildfires	*Transmission –* High voltage lines	Underground transmission lines	$500,000 to $30,000,000 per mile (more for urban areas/new construction)[27,28]
Extreme heat	*Distribution –* Primary and secondary feeders	Install sectionalizing switches to limit customer impacts of a fault	$30,000 to $80,000 depending on the sectionalizing device, voltage class and construction/integration costs
Sea level rise	*Transmission & Distribution—* Substation	Elevate control room, breakers, transformers, switches, etc.	An additional $100,000 to $200,000 for new substations

2.2. Retreat/Redesign

Adaptation measures the involve "Retreat or Redesign" include actions that attempt to site assets out of hazardous locations.

In some cases, it will not be feasible or effective to rely on incremental measures in the face of expected continuous change. More transformational measures, which involve significant asset relocation or system redesign, may be desired. For example, for a coastal substation exposed to increased flooding due to sea level rise, concerns regarding the effectiveness, safety, costs, or feasibility due to site constraints may limit the ability to elevate or harden assets in place. Relocating the substation to an inland location that is not exposed may provide more effective long-term adaptation. Additional examples of measures that involve retreat or redesign are provided in Table 2-2.

[25] Dibra, B., Z. Finucane, B. Foley, R. Hall, R. Damiani, B. Maples, Z. Parker, A. Robertson, G. Scott, T. Stehly, F. Wendt, M.B. Overgaard Andersen, K. Standish, K. Lee, A. Raina, K. Wetzel, W. Musial, and S. Schreck. 2016. Hurricane Resilient Wind Plant Concept Study Final Report. Technical Report NREL/TP-5000-66869.
[26] Matzat, G. 2014. Advanced Offshore Wind Tech: Accelerating New Opportunities for Clean Energy. EPA Office of Energy Efficiency & Renewable Energy.
[27] U.S. DOE. 2016. Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning.
[28] Hall, K.L. 2013. Out of Sight, Out of Mind 2012: An Updated Study on the Undergrounding of Overhead Power Lines. Prepared by Hall Energy Consulting, Inc. for Edison Electric Institute.

Table 2-2: Example retreat/redesign adaptation measures

Retreat/Redesign			
Hazard	Asset Type	Example of Measure	Associated Cost (Where estimates are available)
Sea level rise and storm surge	*Generation* – gas-fired power plant	Select high-elevation site for new construction	
Wildfire	*Transmission* – High-voltage lines	Design alternate transmission routes to avoid wildfire zones	
Coastal storms	*Distribution* – Primary and secondary feeders	Increase the use of distributed generation and storage	

2.3. Accommodate/Manage

"Accommodate/Manage" adaptation measures include strategies that factor the impacts of climate change into operational and design considerations by accounting for impacts, rather than resisting them.

Integrating climate change considerations into planning, design, and procedures can help to ensure that assets and operations effectively accommodate future conditions. For example, installing either additional capacity or high-efficiency turbines at a gas power plant can be used to help account for climate-driven decreases in generating efficiency and increases in demand. Establishing planning protocols that avoid new investments in hazard zones, such as for flooding, which account for potential future conditions, can help to improve system performance. Changes in system design, such as grid segmentation and switch locations or siting of integrated distributed generation assets, can provide additional long-term benefit. Many measures in this category have the effect of increasing the adaptive capacity of systems to respond to adverse impacts.

In addition to asset-based adaptation measures, changes in policies and procedures that improve operations may help reduce impacts from a range of climate hazards. For example, new design or procurement standards that account for future conditions could be developed to support the system's ability to accommodate changes in some hazards, such as temperature-driven reductions in asset capacity ratings. For potential increases in frequency or intensity of storms, more robust emergency response protocols, including planned resources and spares, may be appropriate. See Table 2-3 for additional examples. In many cases, effective operational responses to high-impact, low-probabilty events may be significantly less expensive and more cost-effective than physical hardening measures.

Table 2-3: Example accommodation/management adaptation measures

Hazard	Asset Type	Accommodate/Manage Measure	Associated Cost (Where estimates are available)
Heavy precipitation	*Generation* – Biogas plant	Purchase pumps and implement water removal protocols	
Coastal storms	*Transmission* – Towers	Design alternative transmission routes to avoid riverine flood zones [29]	
Extreme heat	*Distribution* – Entire system	Implement consumer demand reduction programs to reduce peak load[30]	$50 to >$1,000 per MWh

2.4. Monitor

Monitoring climate risks and the effectiveness of adaptation measures over time, provides information that can improve real-time system operations, understanding of evolving risks, and inform design and adjustment of adaptation measures.

Effective monitoring is an important component of any adaptation plan. Monitoring should include climate and weather conditions, as well as asset and system performance. Remote monitoring networks for local meteorological conditions sited at key asset locations and throughout the operating territory can improve real-time system awareness and inform assessments of changing operating conditions. Climate adaptation-specific monitoring may expand routine and/or standardized protocols that can mitigate climate risk. For example, managers of an overhead distribution network may conduct a vegetation management program that mandates inspection and trimming of high-threat trees (which could pose risks during a wind storm or exacerbate wildfire risk) at every portion of the system every two years—potentially reducing risk at a lower cost than expensive hardening measures. In addition, technology integration (such as float switches on the floor of substation) can alert system managers of water intrusion, while SCADA systems can be used to track asset performance and change in operating conditions, including during extreme events. Table 2-4 provides additional examples of monitoring actions.

Table 2-4: Example monitoring adaptation measures

Hazard	Asset Type	Monitor Measure	Associated Cost
Sea level rise + storm surge	*Generation* – All	Secure access to local tide gauge information to track long-term change in water levels	

[29] Rebolini, M., A. Posati, G. De Donà, and P. Berardi. 2013. Rescue Structures Speed Restoration. Published by T&D World Magazine.
[30] U.S. DOE 2016

Hazard	Asset Type	Monitor Measure	Associated Cost
Extreme heat	*Transmission* - All	Track change in annual high temperatures and peak load to determine the need for future capacity additions	
Extreme heat	*Distribution* – Pole transformers	Remote monitoring of distribution transformer load and temperature	

2.5. Policy, Planning, and Capacity-Building

Some of the most important climate adaptation measures are those that take the form of policy, planning, and institutional changes. Measures at this level increase the long-term ability of relevant in-country government and energy-sector actors to systematically account for impacts and risks associated with climate change in energy sector planning. Some measures of this type may be supported by the World Bank in the form of Development Policy Loans (DPL) or technical assistance components included as part of IPF. This category of adaptation measures may in some cases overlap with other categories that incorporate operational measures, such as "monitor" and "accommodate/manage." As reflected in Table 2-5 below, measures of this type are also likely to have cross-cutting benefits spanning different asset types and threat types within the power sector.

Measures in this category may include revision of nationwide standards, mainstreaming of climate data and resilience expertise and considerations in energy planning processes, financial instruments, stakeholder engagement processes around energy sector resilience, and investment in data collection and analysis. As an example, Tanzania and Ghana are adapting the traditional integrated resource planning (IRP) process into an integrated resource and *resiliency* planning (IRRP) process. In doing so, planners in these countries are incorporating climate data and scenario-planning approaches into energy adequacy planning processes, particularly as they relate to hydropower adequacy and the potential for future climate-driven droughts.[31] The World Bank's support for the Belize Energy Resilience for Climate Adaptation Project (ERCAP)—further described in Annex 1—includes several measures in this category, including improving access to meteorological data, support for resilience information dissemination and knowledge-sharing, and developing a new Emergency Response and Recovery plan at Belize's national utility. In addition, financial instruments, such as insurance, can be structured to incentivize investment in resilience measures.

[31] Hellmuth, M.; Cookson, P; and Potter, J, "Assessing Climate Vulnerability for Power System Resilience and Energy Security," USAID, May 2017, https://www.climatelinks.org/sites/default/files/asset/document/2017_RALI_Addressing%20Climate%20Vulnerability%20for%20Power%20System%20Resilience%20%26%20Energy%20Security_Hydropower%20White%20Paper.pdf.

Table 2-5: Example policy, planning, and capacity-building measures

Policy, Planning, and Capacity-Building			
Hazard	Asset Type	Measure	Associated Cost
Sea level rise + storm surge	*Cross-cutting*	Implement requirements that utilities develop storm-hardening plans, and provide technical assistance	
Multiple hazards	*Cross-cutting*	Provide technical assistance to utility staff on the implementation of early warning systems and smart-grid technology	
Multiple hazards	*Cross-cutting*	Update equipment and/or infrastructure design standards to include plausible climate-exacerbated hazard events	

Section 3. Incorporating Climate Risk Management into Project Design

This section outlines a high-level process and principles for climate risk assessment and management for power sector projects. The approach described here is based on a hierarchical model of risk assessment, progressing from a broad-based screening approach that encompasses many different potential hazards, and narrowing to a more detailed assessment of the specific hazards of greatest concern. Risk assessment should feed directly into risk management, identifying key vulnerability relationships and thresholds and helping to determine appropriate and effective adaptation measures based on risks identified. Ideally, climate risk management progresses occurs across the project cycle, and can be incorporated into project feasibility studies and engineering designs, through to operations and maintenance.

Figure 3-1. Progression of Climate Risk Management and Key Questions for each sub-Stage

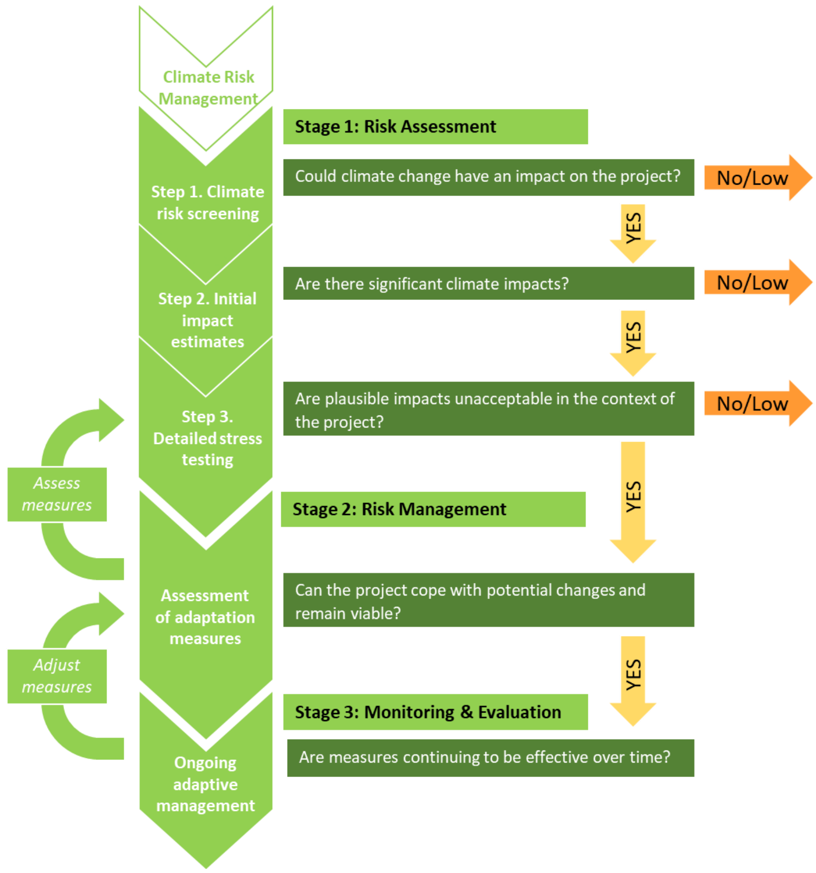


Figure 3-1 provides a schematic of the progression of climate risk assessment and management across the project cycle, as expanded further in this section. This type of hierarchical approach is reflected in the Decision Tree Framework approach the World Bank has previously adopted for analyzing and managing climate risks to water and hydropower projects.[32] This Good Practice Note draws substantially on the Decision Tree Framework and other similar approaches, with adaptations to allow generalization to a broad range of asset types and project circumstances.

Figure 3-1 outlines the progression of each stage: 1) climate risk assessment; 2) climate risk management; and 3) monitoring and evaluation. As climate risk management progresses across the project cycle, task teams can reference the key questions at each sub-stage as a quick guide to the level of detail and key objectives of the sub-stage assessment.

In general, screening-level risk assessment (Step 1) should begin in the early stages of the project identification phase, with more detailed assessment (Steps 2 and 3) occurring during the assessment and/or appraisal stages. Detailed assessment of adaptation measures should take place during the

[32] Mott and MacDonald Group. 2017. Hydropower Sector Climate Resilience Guidelines. Report for the World Bank.

appraisal phase, but identification of potential adaptation measures should occur as early as possible such that they can be considered throughout the design process.

The precise alignment of climate risk assessment with the project cycle will differ from project to project. In cases in which early, high-level assessments indicate significant risks or potentially high-cost adaptation measures, project teams may choose to accelerate the risk assessment and management process. Furthermore, not all World Bank projects follow the same progression, and in some cases the World Bank may become involved in a project at a later stage (e.g. after pre-feasibility or feasibility analysis has been completed). In non-standard cases, climate risk assessment should be retroactively incorporated into these analyses to the greatest degree possible. As such, the steps discussed here should be viewed as guidelines, rather than a rigid progression.

While recommendations in this section are framed primarily with physical infrastructure in mind, the concepts underlying this process also apply to the identification of projects for policy, planning, and capacity-building toward power sector resilience, such as those that may be supported under Development Policy Loans, PforRs and TA components of IPFs. Identification of appropriate energy resilience projects in this category should similarly follow a hierarchical process proceeding from climate risk screening ("Does this country face plausibly significant climate change risks to the power sector?"), to a more detailed understanding of potential climate impacts, to assessment of the potential benefits of proposed policy, planning, and capacity-building measures and long-term planning for continued effectiveness.

In general, improved sensitization of governments and local stakeholders to the costs and benefits of climate change adaptation will improve the ability of future projects to effectively incorporate adaptation strategies.

While this section presents best practices and considerations around approaches for assessing climate change risks and mitigation measures, the diversity of project types, adaptation types, and specific contexts means that there is not a single one-size-fits all methodology for climate adaptation. Task teams should consider climate risks for all projects, but the specific risk assessment and management approach may vary based on project-specific details. For example, a 7 MW solar farm for which storm-hardening measures (e.g. stronger anchorage hardware) would be relatively inexpensive may not warrant climate risk analysis of the same complexity (and cost) as a large-scale investment in transmission infrastructure. As such, task teams should manage climate risk using the approach best-suited to the specific project. A fuller set of considerations in selecting assessment approaches is outlined in the box below.

Guiding Factors for Task Teams in Selecting Assessment Approaches

Cost/complexity of analysis: More complex and analytically intensive assessment approaches require more time and resources, either directly from task teams or from external consultants. This is one benefit of the use of a tiered/hierarchical approach to risk assessment and management, which begins with less complex/costly analyses and only progresses to more rigorous analyses if those are warranted by identified risks.

Magnitude of risk: High-value assets, high-criticality assets, and assets facing significant hazards are all likely to warrant a more analytically intensive approach to assessment than lower-value, lower-hazard assets.

Cost of adaptation measures: High-cost adaptation measures will require a greater degree of justification. If effective measures are low-cost and low-regret, a less intensive analytical approach may be justifiable.

Timeline: Time available for assessment may vary from project to project, and in some cases available calendar timeline may influence the feasible scope of assessment.

Data availability: In some cases, the selection of an assessment approach will be driven by whether sufficient relevant data is available. For example, a cost-benefit analysis of system hardening to reduce outage probability would require estimates of outage costs that can be avoided. If access to representative data from a local utility is not available, a less data-intensive method may be preferable.

Managing climate risks (both the process of assessment and the actual implementation of adaptation measures) can have significant associated costs. The purpose of climate risk management is to avoid even larger costs associated with a lack of preparedness for future hazards—making it a fully justified and cost-saving endeavor in the long-run. Task teams should seek funds from appropriate sources, including the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) and the Green Climate Fund (GCF) (See Annex 5 for more information on Adaptation Funding Resources).

3.1. Stage 1: Climate Risk Assessment

Climate risk assessment and management should be an iterative, tiered process that occurs at progressively higher levels of detail over the course of the project cycle, with the most detailed assessment reserved for the most relevant and critical risks. As the project cycle progresses, particularly for highly capitalized projects, the hierarchical approach to analysis of climate risks and adaptation measures will naturally become more (or less) information intensive as project planners' move from scoping towards feasibility and engineering designs. The level and type of analysis determines in large part the level of information and data required, including the level of technical detail and temporal and spatial scope of the assessment Figure 3-2 provides examples of different types of analysis on a spectrum from high-level rapid screening (e.g. use of readily available storm surge information) to detailed, highly involved analyses (e.g. advanced storm surge modeling incorporating sea level rise proejctions).

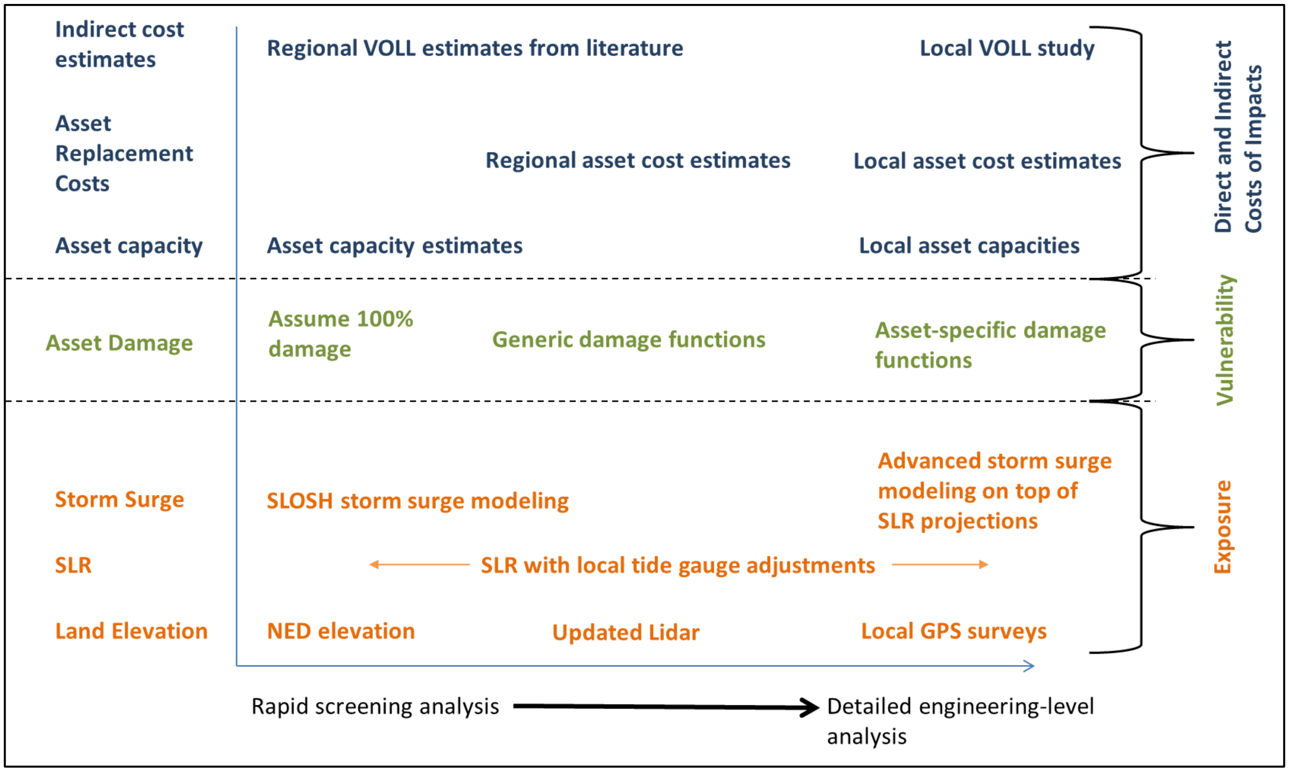
Climate risk assessment should encompass three primary elements, presented here with definitions from the Intergovernmental Panel on Climate Change (IPCC) modified for the power sector:

- **Exposure**: The presence of power sector assets in places and settings that could be adversely affected by climate variability or change
- **Sensitivity**: The degree to which a power sector asset or system is affected, either adversely or beneficially, by climate variability or change
- **Adaptive capacity**: The ability of power systems, institutions and managers to adjust to potential damage, to take advantage of opportunities, or to respond to consequences[33]

Each level of climate risk assessment should assess these elements, with an increasing level of detail as the magnitude of potential impact grows. Climate change risk assessment should be "bottom-up" in the sense that it begins with the needs of decision-makers and analyzes a wide range of potential future climates based on critical values and thresholds (rather than relying on the assumptions of a particular model).[34] For example, assessment of extreme temperature impacts on transformers should begin with the critical temperature and load thresholds beyond which transformers fail or sustain damage. Assessment should be tested against all plausible scenarios, not just the most likely ones.

[33] IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability, Annex II, Glossary, p. 1772.
[34] Ray, P. and C. Brown. 2015. Confronting Climate Change Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework. World Bank.

Figure 3-2: Examples of information needs for climate risk assessment of different levels of detail. This figure presents sample analytical methods for climate risk assessment, increasing in detail (and cost/time required to apply) from left to right. The vertical axis includes information categories necessary for key aspects of a climate resilience assessment: the exposure (orange), vulnerability (green), and costs of impacts (blue). SLR is sea level rise, VOLL is value of lost load, and NED is national elevational dataset. Source: U.S. DOE, 2016.



Climate Risk Assessment Step 1: Climate Risk Screening

Key question: Could climate change have an impact on the project?

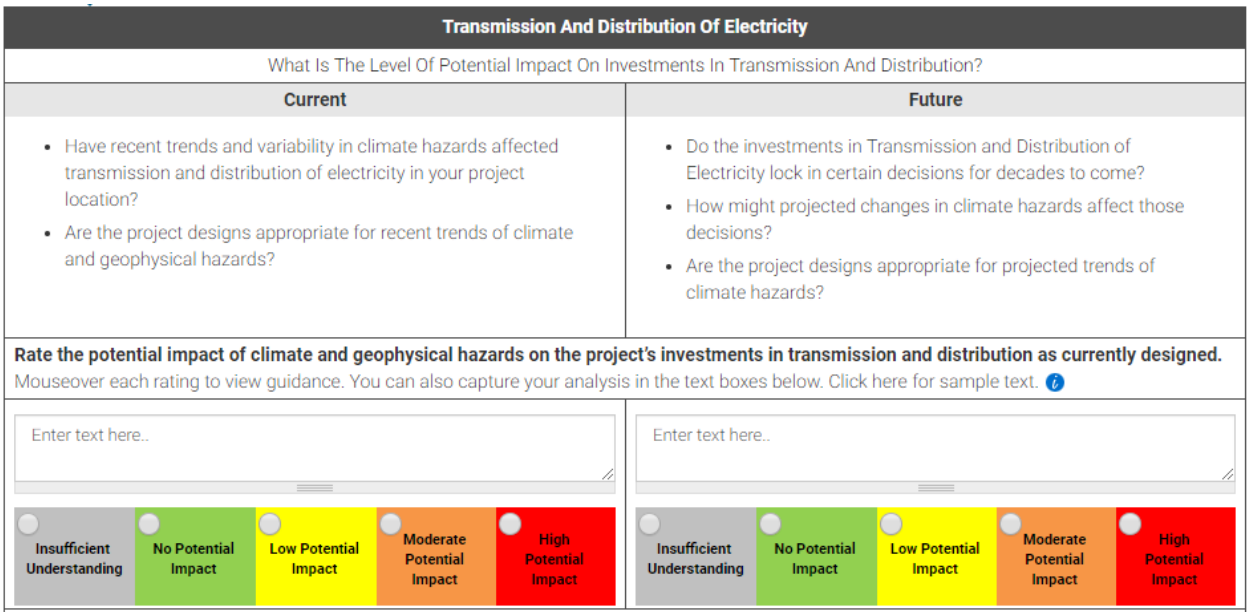
The first step in climate risk assessment is an initial screening for climate risk. This step evaluates qualitatively whether climate change is a risk to a project, and through what impact mechanisms (e.g. extreme heat reducing transformer capacity, potential flooding) that risk may manifest. This step should be undertaken at the earliest possible point in the project cycle, ideally in the Concept phase as part of pre-feasibility assessments. Consideration of potential impacts during the screening assessment should be wide-ranging, including all plausible climate hazards. It should also include broad consideration of potential impact mechanisms, including indirect impacts that may be related to failures or impacts elsewhere within a networked system.

The Climate and Disaster Risk Screening Tool is one of several tools that can be used to guide project teams in this process (see Figure 3-3).[35] Completion of the screening process is mandatory for all International Bank of Reconstruction and Development/International Development Association

[35] World Bank Climate Risk Screening Tool. Available at: https://climatescreeningtools.worldbank.org.

projects.[36] The Climate and Disaster Risk Screening Tool provides a sector-specific structure for qualitative assessment of potential climate risks to project. It directs project teams to draw historical and projected future climate information from the World Bank's Climate Change Knowledge Portal[37] (CCKP) in order to provide initial potential impact ratings, pointing users directly to the country of interest and relevant variables, which include both annual averages and extreme events. A list of climate risk screening tools is provided in Annex 6.

Figure 3-3: Sample Screenshot from the World Bank's Climate and Disaster Risk Screening Tool



The screening process performs an initial survey of the potential climate exposure, sensitivity, and adaptive capacity of a project. The level and type of assessed risk during the screening phase should inform the rigor and emphasis of the more detailed risk analysis that follows, with risks analyzed in this stage estimated quantitatively at later stages.

It is important to note that the application of screening tools to rate the level of potential impact contains elements of subjectivity, dependent in part upon the expertise of the individual(s) applying the tool, and underlying uncertainties. It can be difficult for non-experts to take into account uncertainty in scientific knowledge, or to estimate the probability or consequences of hazard and impact. Risk screening can result in 'false positives' or 'false negatives' where risks are underestimated or not flagged. The latter case can be especially damaging, as subsequent more detailed risk assessment will not be undertaken. For these reasons, it is recommended that adequate time is alloted, and appropriate expertise in hazard idenitification and analysis is incorporated at some stage within the risk screening process, in order to improve results.

Climate Risk Assessment Step 2: Initial Impact Estimates

Key question: Are there significant climate impacts?

[36] World Bank Climate Change Group. Reference Guide on Adaptation Co-Benefits.
[37] Climate Change Knowledge Portal. Available at : https://climateknowledgeportal.worldbank.org/

After the screening process, project teams should proceed to generate initial quantitative estimate of the potential impacts associated with the climate change risks identified as being of potential concern. Moving beyond the qualitative screening stage, project teams should attempt to quantify the magnitude of risk from potential climate impacts relative to other project risks.

For example, initial analysis of a transmission line project would likely include an estimate of the potential hottest 3-day average temperature during the asset's life, and the simultaneous impacts of that temperature on peak load and on heat-related reductions in the asset's capacity.

At this stage, approximations of future climate conditions should be best estimates informed by available climate data (including historical data and related trends), but should not require extensive development of projections. Climate data used for an initial analysis may include data from the World Bank screening tool (used in a quantitative fashion, as opposed to initial qualititative screening), projections from national-level climate assessments. Where better data is not available, rough estimation may rely on historical extreme events extrapolated against an elevated baseline (e.g. adding projected baseline temperature change on top of the hottest heat event on record and/or assuming the heat event lasts 30 percent longer). In many cases, quantitative analysis conducted as part of this phase is accomplished through climate change-informed adjustments to models (e.g. load models) that are already part of standard project feasibility analysis.

The purpose of the analysis at this stage is not to accurately quantify the range of potential risks, but to assess them at an order of magnitude. This allows for the identification of climate impacts for further consideration, as well as for an early sense of what type of adaptation measures may be appropriate.

Climate Risk Assessment Step 3: Detailed Risk Assessment and Stress Test

Key question: Are plausible climate risks unacceptable in the context of the project?

If the preceding analysis uncovers climate risks of a potentially significant magnitude, these risks should be assessed at a high level of detail. In many cases this analysis will be highly complex and will likely require a collaborative approach amongst power sector specialists and external consultants or qualified internal experts

As described in Section 1, this analysis should use best practices for incorporating climate information into project risk assessment- including the use of historical climate information, and abroad range of climate projections and scenarios in order to capture the full range of uncertainty in future conditions for the decision relevant time frame(s) and climate-related variables.

Climate information can be coupled with power sector information, modeling and analysis, in order to test the sensitivity of the project (or power system) to a range of projections. For example, once the range of plausible projections and relevant climate variables have been identified, they could be incorporated into modeling of project performance and assessed against proposed project characteristics. An assessment of a gas-fired power plant might evaluate the degree to which peak-coincident capacity during a heat wave could be reduced by heat-related efficiency losses across a range of potential scenarios, in order to determine whether future conditions may cause the project to fall short of its required performance. Assessment of a coastal substation could determine whether the maximum plausible storm surge, combined with sea level rise, is likely to inundate equipment based on planned designed characteristics.

Some power sector analysis will lend itself to relatively easy integration of climate information into existing analysis and models, given climate-related information is already taken into account (e.g., effects of increasing temperature into load forecasting, or assessment of flood hazard exposure at proposed project sites); other analyses and models may need to be significantly modified, or new approaches developed, in order to assess the level of potential climate risk. Adding to the difficulty, most engineering manuals do not (yet) reflect updated approaches to incorporate climate risk into power feasibility and design studies. For these reasons, engaging experts will be critical to capturing plausible climate risks.

A broad range of climate risk assessment methods is included in Annex 6. These methods are not only used to assess the level of climate risk to a certain project, but also to evaluate the effectiveness of adaptation measures in reducing climate risk. For projects with long lifespans, it will be important to engage experts on on the selection of climate scenarios and the methodology for assessing project resilience; in order to account for climate uncertainty in decision-making.

Based on the results of this analysis, the consequences of the impact scenarios identified relative to acceptable metrics of performance should be assessed against their likelihood in order to determine the need for risk mitigation measures. It is important to note that this is not a fully probabilistic analysis, as fundamental uncertainties about climate impacts make discerning probabilities impossible in some cases.[38] Rather, assessments should be made of whether plausible impact scenarios are acceptable or unacceptable in the context of a project.

3.2. Stage 2: Climate Risk Management: Assessment of Adaptation Measures

Key question: Can the project cope with potential changes and remain viable?

Based on the results of the climate risk assessment process, project task teams and the asset managers should develop a strategy for reducing climate risks to a level that is acceptable based on project performance metrics. The Bank is developing of a set of process-based metrics to measure the extent to which projects are designed to account for climate risks and other uncertainties, and to support resilience building outcomes in a given community, ecosystem, or country.[39]

Addressing climate risk often involves the evaluation, selection, and implementation of multiple adaptation measures, as described in Section Section 2. Adaptation measures should be considered for each relevant climate risk or combination of risks identified. Annex 1 of this document contains a catalog of adaptation measures that provides a starting point for task team leaders in selecting adaptation measures. Task teams may also undertake detailed consultation with engineering staff and external consultants, depending on the scale of relevant risks and the difficulty of addressing them.

In some cases, adaptation measures may be low-cost and low-regret, allowing for a simple decision to implement them. For other measures, however, there will be trade-offs to navigate in terms of cost

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[38] Lempert, R., N. Nakicenovic, D. Sarewitz, and M. Schlesinger. 2004. Characterizing climate-change uncertainties for decision-makers. An editorial essay. Climatic Change 65(1):1-9

[39] Hallegatte, S. and N.L. Engle. 2019. The search for the perfect indicator: Reflections on monitoring and evaluation of resilience for improved climate risk management. Climate Risk Management 23:1-6. doi: 10.1016/j.crm.2018.12.001

and/or project performance. Key strategies for climate-resilient infrastructure are outlined in the side-bar, and include making better decisions in the face of climate uncertainty.[40] For example, project teams can apply risk management tools and approaches that are designed to idenfity "robust" adaptation strategies. These methodologies can help task teams to prioritize strategies that improve the ability of projects to perform well over a wide range of climate and non-climate uncertainties rather than optimizing performance under a narrow set of conditions.

Seven Strategies for Climate-Resilient Infrastructure

1. Make better decisions in the face of uncertainty.
2. View infrastructure systemically.
3. Take an iterative, multihazard approach.
4. Improve and inform cost-benefit analysis (CBA).
5. Mainstream nature based infrastructure.
6. Jump-start resilience with immediate actions.
7. Plan now to build back better.

Robust adaptation strategies can take many forms and be classified as "no-regret," reversible and flexible, incorporating safety margins, employing "soft" solutions, or reducing decision timeframes (Hallegatte 2009). At the same time, robustness can increase project cost, and it is economically and physically impossible to design a project that can perform under the full range of uncertainties. In view of this, vulnerability thresholds are commonly established for robustness to many, but not all, possible climate futures.[41] Given damages and impacts typically increase as a function of stressor intensity (e.g., see Annex 3), identifying thresholds requires determing an acceptable level of risk. For example, adaptation measures may aim for robustness to extreme heat events reflecting the 90th percentile severity of model projections, accepting that events beyond that are too costly to plan around given the significant uncertainties involved. Appropriate risk thresholds for resilience investments (e.g. a Category 3 versus Category 4 storm, or a 100-year versus 500-year flood) are highly context-specific.

Thresholds for damaging conditions may vary widely across different asset types: the wind velocity that is likely to damage a solar array may differ substantially from the velocity that is likely to damage a transmission line. Risk threshold selection is also guided by various considerations including costs, expected life of the investment, criticality of the investment, and others. As such, this note does not provide prescriptive recommendations on specific risk thresholds, as these will vary across projects.Methods for evaluating adaptation measures are likely to vary based on a number of factors, including availability of information on climate-related hazards and the effectiveness of adaptation measures, types of impacts considered (e.g. societal impacts versus direct project impacts), and total cost and criticality of the project in question. Task teams should refer to World Bank guidance on financial, economic, and risk analysis for incorporating costs of adaptation measures into the analysis. If necessary, these separate pieces of this note should be updated over time based on task team feedback to ensure that they provide sufficient information relevant to climate adaptation. Tools and methods for

[40] Hill, Alice C., Douglas Mason, Joanne R. Potter, Molly Hellmuth, Bilal M. Ayyub, and Jack W. Baker. Ready for Tomorrow: Seven Strategies for Climate-Resilient Infrastructure. Hoover Institution, 2019.
[41] Garcia, L.E., J.H. Matthews, D.J. Rodriguez, M. Wignen, K.N. DiFrancesco, and P. Ray. 2014. Beyond downscaling: a bottom-up approach to climate adaptation for water resources management. AGWA Report 01. Washington, DC: World Bank Group.

evaluating adaptation measures are discussed in brief in the box below, and at further length in Annex 6.

Methods for Evaluating Adaptation Measures

Cost-benefit analysis is a familiar framework for most decision-makers, and can be used effectively to assess the benefits of climate adaptation in cases where those benefits can be quantified. However, accurately quantifying the projected benefits of climate adaptation measures can be challenging, particularly when benefits are distributed across multiple parties, or when expected climate impacts or the impact reduction associated with adaptation measures are unknown or uncertain.[42]

Multi-criteria analysis is useful in evaluating adaptation measures where the benefits cannot be fully valued in financial terms. For example, planners may struggle to accurately value the benefits of avoided electricity outages where estimates of the societal damages associated with power outages are not available. Multi-criteria analysis allows for transparent side-by-side comparison of multiple criteria, which may be quantitative in nature (e.g. results of a cost benefit analysis, number of customer outage hours) or qualitative factors rated on a quantitative scale (e.g. 1-5).[43]

Scenario analysis is a non-probabilistic method of assessing risks in a variety of different potential futures. It involves the side-by-side consideration of multiple potential risk scenarios that cover the range of plausible assumptions. It has the benefit of being robust to a variety of potential futures, via the explicit consideration of impact and adaptation scenarios that may be low probability, but would result in significant impacts.[44]

These measures and others are discussed in additional detail in Annex 6.

Evaluation of adaptation measures can often be reviewed during an iteration of the later, more detailed stages of the risk assessment process (as reflected in Figure I-1). Where the impacts of adaptation measures can be quantitatively estimated, the modified project can then be re-assessed against the relevant climate risks to determine whether the selected measures result in a more viable project that meets acceptable criteria for performance and cost under all plausible climate change scenarios.

In the process of identifying and evaluating adaptation measures, Task Teams should also seek to establish a best estimate of the incremental costs of climate adaptation. Knowledge of incremental costs is important for the appropriate attribution of climate adaptation co-benefits to a project under the World Bank's climate finance tracking/adaptation co-benefits assessment framework (see Section 4). The development of incremental cost estimates involves establishing a counterfactual "no adaptation" cost for comparison with the actual project cost. These incremental costs will sometimes be difficult to calculate beyond the level of an informed estimate (e.g. the cost of a 4-foot floodwall versus a 6-foot floodwall). However, the process of developing these estimates can be substantially simplified and

[42] Chiabai et al. 2015. Using costs and benefits to assess adaptation options. EconAdapt.
[43] U.S. DOE. 2016. Climate Change and the Electricity Sector: Guide for Assessing Vulnerabilities and Developing Solutions to Sea Level Rise.
[44] Task Force on Climate Related Financial Disclosures. 2016. The Use of Scenario Analysis in Disclosure of Climate Related Risks and Opportunities.

improved by conducting analysis during the course of project design, rather than in later stages of the project.

It is important to note that implementation of resilience measures may not need to occur immediately. For example, if plausible heat-related impacts on a substation are not projected to a degree that poses risks until 2040, it may be more cost-effective to delay expansion of transformer capacity until shortly before that time.

Guiding Factors for Selecting Adaptation Strategies

While priorities for the selection of adaptation measures and methodologies for evaluating them are likely to vary significantly across projects, general factors to consider in selecting adaptation strategies include:

Cost: Adaptation measures vary widely in the incremental cost they impose on projects, from relatively affordable to prohibitively costly.

Anticipated damages avoided: The primary function of adaptation measures is to mitigate anticipated negative impacts on investments. This includes both direct impacts (e.g. physical damage to the asset itself) and indirect impacts (e.g. societal loss of well-being and economic output due to power outages). Various assessment approaches such as cost-benefit analysis and multi-criteria analysis can help estimate avoided damages and compare them to potential costs.

Robustness: Robust adaptation measures are effective across a range of potential climate change and hazard scenarios, reducing the potential impact of uncertainty.

Flexibility: Projects designed to have flexible adaptation characteristics can be adjusted over time depending on which hazard scenarios materialize (e.g. indoor equipment has enough overhead clearance such that it can be elevated in the future if flooding becomes more severe).

Co-benefits: Some resilience measures may provide benefits outside of avoiding climate-related damages, such as greenhouse gas emissions reductions associated with distributed solar generation, or public green space created as a flood embankment.

3.3. Stage 3: Ongoing Adaptive Management, Monitoring, and Evaluation

Ongoing adaptive management, monitoring, and evaluation should occur throughout the life of the project, and planning for these activities should begin during the project design phase.

Key question: Are measures continuing to be effective over time?

Over time, changes in climate and weather patterns will manifest and a better understanding of local conditions and changes may emerge, energy system technology will change, and economic and demographic trends will influence demand. As such, climate change resilience plans should allow investments to respond adaptively to new information and observed change. To facilitate this, development of plans and technical and operational systems to monitor the following variables is recommended:

- **Environmental change:** Monitoring of relevant indicators of environmental change can allow for more effective and cost-efficient adaptation to climate impacts. For example, monitoring of average and extreme levels at a tide gauge proximate to a coastal substation can provide asset managers with information as to whether flooding threats are more or less severe than expected, providing information about whether and when a substation may need to be waterproofed, elevated, or relocated.
- **Asset performance:** Monitoring of asset performance relative to expectations can provide information on whether resilience measures require adjustment. For example, if heat-related distribution transformer failures during heat waves exceed expected values, re-assessment of distribution transformer standards may be worthwhile.
- **Technological change:** Periodic reassessment of the state of available technology, especially as global emphasis on climate resilience increases, may reveal opportunities for more effective or cost-efficient resilience.

Plans for monitoring and responding to change may involve periodically scheduled assessments (e.g. every 5 years) or pre-set thresholds that trigger action or re-evaluation (e.g. predefined sea level triggers). For further information on adaptive planning, project teams may wish to reference the growing literature on "flexible adaptation pathways."[45] The flexible adaptation pathways framework, which has strongly influenced several governments that are leading on infrastructure climate resilience planning (including California, New York City, and London), provides a thresholds-based framework for low-regrets adaptation in the face of uncertainty.[46]

These monitoring efforts provide important inputs to project evaluation, providing information the effectiveness of climate adaptation and resilience measures relative to original expectations, and their overall benefits to the project and population served. Task teams should include assessment of the implementation progress and performance of climate adaptation measures in project evaluation plans.

Perhaps most importantly, tasks teams should ensure that climate risk considerations, including the results of risk analyses, are effectively communicated to clients. Sufficient client understanding of the climate-related risks associated with a project is important for effective ongoing risk management.

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[45] For more information on flexible adaptation pathways, see "Haasnoot et al. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 23(2): 485-498" and "Bruzgul et al. 2018. Rising Seas and Electricity Infrastructure: Potential Impacts and Adaptation Actions for San Diego Gas & Electric. California's Fourth Climate Change Assessment, California Energy Commission (2018). Publication Number: CCCA4-CEC- 2018-004."

[46] California Climate Safe Infrastructure Working Group. 2018. Paying It Forward: The Path to Climate-Safe Infrastructure in California. California Natural Resources Agency.
Reeder, T. and N. Ranger. 2011. How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project. World Resources Report.
New York City Mayor's Office of Resiliency and Recovery. 2018. Climate Resiliency Design Guidelines.

Section 4. Assessing Climate Adaptation Co-Benefits in the World Bank Framework

The World Bank tracks financial resources that it invests in activities that provide "climate co-benefits" in terms of the mitigation greenhouse gas emissions or that assist in adaptation to climate change. The World Bank has set a goal for 28 percent of its investments to be climate-related by 2020, with a significant increase in financing support for adaptation in FY21-25. All projects should be assessed to determine whether they contain aspects that can be counted as adaptation co-benefits. Wherever possible, adaptation investments that may significantly increase greenhouse gas emissions associated with a project (e.g. installation of additional gas-fired capacity) should be avoided.

The World Bank uses the Joint Multilateral Development Bank Methodology for tracking climate change co-benefits. While task teams are not responsible for tracking climate change co-benefits (this responsibility falls to the Climate Change Group) task teams are required to describe how project design has considered climate change. In order to align with the co-benefits methodology, task teams should ensure that descriptions of climate change considerations clearly reflect the following three elements (known as the "three steps"):

- **Context:** How is climate change affecting or expected to affect the local context of the project or the project itself?
- **Intent:** How does this project explicitly intend to address climate change risk?
- **Linkage:** How do project activities link to identified climate change vulnerabilities?

Adaptation co-benefits are counted based on the incremental cost of measures that directly address climate change impacts. As such, for many projects, climate adaptation co-benefits will reflect only a portion of project costs. For example, if a project team determines that future projections for extreme heat require higher-capacity transformers than historical temperatures would warrant, only the incremental cost of those higher-capacity transformers should be counted as a climate change co-benefit, rather than the entire cost of the transformers. Thus, the development of incremental cost estimates involves establishing a counterfactual "no adaptation" cost for comparison with the actual project cost. In the transformer example, tracking the incremental cost would involve documenting price estimates for both project design options in the course of assessing adaptation measures. Incremental cost calculation can also be more complex than comparison of different onsite adaptation measures. For example, a Task Team may choose to re-site a solar generation facility on higher ground due to the results of a sea level rise risk assessment. Any additional cost associated with this new site should be documented and recorded as an incremental cost.

Other projects—such as a local microgrid designed to provide backup power to a hospital in the event of a power outage—may have their *entire* costs counted as climate adaptation co-benefits, if the entire investment can be shown to have a linkage to an identified climate change vulnerability. Similarly, projects that are specifically targeted towards capacity-building or policy change in an area that contributes toward energy resilience—such as capacity building in power-sector planning at a country's Department of Energy—may be 100% attributable as adaptation co-benefits.

With attribution of co-benefits in mind, project teams should make clear in project documents which specific project components and sub-components were partially or fully intended to address climate change impacts, and should clearly record and justify their best estimates of the incremental costs associated with those measures. While estimating incremental adaptation costs may be challenging in some cases, project teams should make efforts throughout the process to note the 'no-adaptation' alternative and estimate its costs as a point of comparison for the final design. Section 2 and Annex 4 contain some illustrative information about the costs of adaptation—though costs may differ substantially depending on local context. The Temane Regional Electricity project in Mozambique, described in further detail in Annex 1, provides an example of a project that estimated incremental costs of adaptation—in this case the incremental costs of storm-hardening of transmission and substation infrastructure was estimated to be 20%.[47]

In general task teams can significantly simplify the process of estimating incremental costs through documenting estimated costs throughout the process of assessing adaptation measures. Estimating order-of-magnitude incremental costs should be feasible for project teams that are are actively considering this requirement from the beginning of the project cycle.

Some additional limitations to co-benefits assessment for adaptation are outlined in the box below.

Limitations of Co-Benefits Assessment for Adaptation

The World Bank Group's Action Plan on Climate Change Adaptation and Resilience (2019) notes several deficiencies of the co-benefits assessment:

- It underestimates adaptation co-benefits given only the incremental costs of adaptation measures are counted as adaptation co-benefits.
- It fails to capture high-quality activities that may have low, zero, or even negative costs (for example, climate resilient designs that cost less than the alternatives).
- It fails to capture the bidirectional nature of adaptation and development co-benefits because it emphasizes the benefits of development actions for adaptive capacity at the expense of capturing adaptation benefits to development.

The information generated in the progressive risk assessment and management process described in Section 3 results in information that can fully substantiate the above assessment of adaptation co-benefits, including context, intent, and linkage. For example:

- Information from initial risk screening and assessment of potential vulnerabilities, often performed at the *identification* and *assessment* stages of the project cycle, can inform the *context* portion of the narrative, indicating how climate change may affect the project or it's local context.
- Description of the risk assessment process and the carrying forward of its results into specific adaptation actions in the risk management process, in line with the *assessment* and *appraisal* stages of the project cycle, establishes *intent* to adapt to climate change.
- The *linkage* component of the narrative can be directly informed by actions taken in the risk management process, which by its very nature establishes a linkage between climate change

[47] Miyamoto International. 2019. Increasing Infrastructure Resilience Background Report. World Bank Group. #7189546 Overview of Engineering Options for Increasing Infrastructure Resilience. Available at: http://documents.worldbank.org/curated/en/620731560526509220/pdf/Technical-Annex.pdf

impacts and actions taken to mitigate them, and generally applies to the *appraisal* and *implementation* stages of the project cycle.

Task teams should seek to provide as much information as possible relevant to this process as part of project documents. This narrative will inform the evaluation performed by the Climate Change Group. The box below provides an example of how the risk assessment and management process can inform the “Three Steps” narrative. See Annex 1 for case studies that futher illustrate this process.

Energy Sector Example of the "Three Steps"

In this hypothetical example, the World Bank is supporting the development of a transmission line in Tanzania that will serve projected growth in electricity demand in a coastal area.

Context

Example: Climate change is likely to have multiple significant impacts that are relevant to transmission lines within the southeastern coastal region of Tanzania where this project is located. The climate risk screening, conducted as part of the project concept stage, included 11 climate hazards, and identified 2 for detailed stress-testing.

1) **More frequent and severe extreme heat events:** Climate model projections indicate that heat waves in Tanzania may become significantly more frequent and intense. The projected 3-day annual average maximum temperature in 2050 is 38°C, compared to a historical average figure of 36° C. Extreme heat events, especially multi-day events with cumulative thermal loading, cause both an increase in demand for power for cooling and a decrease in the capacity of transmission lines.
2) **More frequent and severe wildfires:** Historical data on wildfire in the vicinity of the planned project over the past two decades demonstrate that the project is located in a wildfire-prone region. A review of relevant literature suggests that wildfire in this region may become more frequent and severe as a result of climate change. Wildfire poses a risk to transmission lines, as it can cause severe damage and even collapse of transmission towers.

Intent

Example: Climate change is anticipated to have significant potential impacts on the region that this transmission project is intended to serve, as well as on the project itself. Given the importance of resilient and reliable power, particularly during or in the aftermath of extreme events, this project included a detailed risk assessment and risk mitigation process during the appraisal stage. As a result, the project has been designed in a way that anticipates and minimizes the risks that climate change poses to its physical integrity and its ability to fully serve peak demand.

Linkage

Example: This project includes several specific design measures to build resilience to climate-related risks.

i) In order to mitigate the risk of insufficient capacity during an extreme heat event, the project design was modified to increase total transmission capacity by 14 percent. This capacity increase reflects both the heat-related capacity losses and the increased demand for cooling associated with the high end of the plausible range of severe heat events in 2040 (the estimated 1% annual probability heat event based on an RCP 8.5 90th percentile scenario). The incremental cost of this climate-related upgrade resulted in a 10% increase in the total cost of the project.

ii) Assessment of wildfire risk indicated that the project site transverses an area with a history of wildfire, which may become more frequent and severe in the future. To mitigate this risk, ongoing management protocols for the project were updated to include an enhanced vegetation management plan, which will periodically remove vegetation with high fuel potential that is located in close proximity to the transmission line. The ongoing incremental cost of this vegetation management plan is amounts to a doubling of typical vegetation management costs.

Annex 1. Case Studies

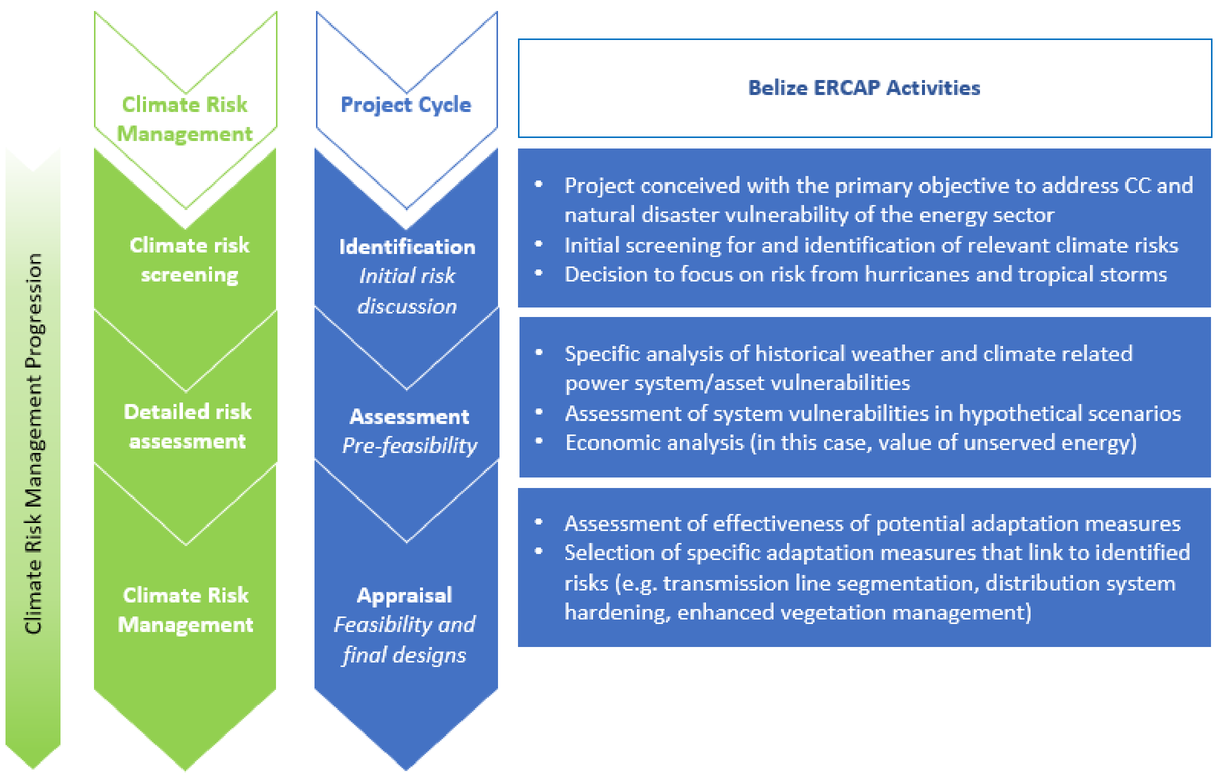
Belize Energy Resilience for Climate Adaptation Project

Background

The World Bank is supporting the government of Belize and Belize's national electricity utility in an effort to increase the resilience of Belize's power system to impacts from coastal storms. This project, the Belize Energy Resilience for Climate Adaptation Project (ERCAP), consists of a set of activities funded by $8 million (USD) in grants to the government of Belize and the country's national electric utility, Belize Electricity Limited (BEL).[48]

This project is notable for the fact that building resilience to climate-related hazards is its primary and explicit goal, and that it was designed as a demonstration of effective power sector resilience measures. 100 percent of funds allocated to this project are counted as climate adaptation co-benefits. Figure A1-1 summarizes the progression of climate risk assessment and management across the project cycle stages.

Figure A1-1: Belize ERCAP Activities by Stage of Risk Management Process and Bank Project Cycle



Risk Assessment

The risk assessment progressed from climate risk screening to a more detailed risk assessment, the latter of which focused on impacts from coastal storms and identified specific vulnerabilities.

[48] World Bank, Project Appraisal Document (P149522): Energy Resilience for Climate Adaptation Project, 2016, (Report No: PAD1366).

Climate Risk Screening

Several potential climate risks were identified during project conceptualization, including: sea level rise, changes in temperature, changes in rainfall patterns, and changes in storm activity.[49] A consultant was engaged to undertake a detailed screening of climate change risks to Belize's energy sector,[50] using tools developed by the World Bank's Energy Sector Management Assistance Program (ESMAP). The screen identified 23 risks, 14 of which were rated as 'very high' or 'high.' Risks flagged as significant to power generation, transmission, or distribution included rising sea levels, more severe hurricanes and tropical storms, volatility in rainfall patterns, increased temperatures, and increased severity of droughts.

Detailed Risk Assessment

Based on the results of the initial climate risk screening, a decision was made to focus in on storm impacts to the power system. A more detailed analysis of the impact of recent historical hurricane and tropical storm events on Belize's power system was undertaken.[51] The analysis, supported by data from BEL, assessed the impacts of three storms that occurred between 2007 and 2010 and the power system vulnerabilities that those impacts revealed. Historical data was presented as an explicit indicator of potential future impacts that "may become even more severe" as a result of climate change, noting that storms have already become more frequent and longer in duration.

The historical analysis demonstrated the economic magnitude of extreme weather impacts, providing an evidence-based grounding for assessment of potential future sector-specific impacts due to climate change impacts. Cost-benefit analysis was not utilized, since the project was conducted for demonstration purposes and detailed future cost projections were not readily available. Instead, unserved energy demand for each event was estimated based on the differential in dispatched electricity following each storm impact event relative to typical dispatch. These economic estimates were intended to provide "a proxy for the development setbacks that arise from extreme weather events due to the vulnerabilities that exist in the power system in Belize."

The analysis identified specific points of failure in the power system that were associated with outages in each storm, including transmission and distribution line and pole/tower failures associated with high winds and fallen trees. This allowed for the identification of asset types with a significant number of failure events and of high-impact points of failure. The high-impact points of failure included insufficiently segmented transmission lines leading to cascading outages, distribution system failures resulting from high winds and/or contact with vegetation, and others. In addition, consultation with BEL indicated operational vulnerabilities, including a less-than-reliable communications system, *ad hoc* restoration efforts, and insufficient meteorological and hydrological data.

Risk Management

Based on the results of the risk assessment process, the Task Team identified adaptation strategies to address priority risks through design.

For the transmission system, a hypothetical analysis was undertaken as part of the detailed risk assessment,[52] with the goal of locating specific points of transmission system vulnerability and testing the effectiveness of different adaptation measures at reducing outages. The performance of the enhanced network (incorporating adaptation measures) at

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[49] World Bank. Project Information Document for Energy Resilience for Climate Adaptation, 2016 (Report No.: PIDC3412).

[50] Acclimatize. 2016. "Building Climate Resilience in Belize's Energy Sector" prepared for the Bank, which utilized an energy adaptation toolkit developed by Bank's Energy Sector Management Assistance Program (ESMAP).

[51] Jayawadena M., B.G. Serna, and J.J. Han. 2016. The Power System in the Eye of the Storm: The Call for Energy Resilience and Climate Adaptation in Belize. The World Bank Group.

[52] The Project Appraisal Document (PAD)

reducing outages given historical and potential future storm events was compared to the performance of the existing infrastructure configuration. The analysis included testing measures at the transmission system vulnerability points identified in the risk assessment, to determine the best locations where infrastructure hardening and system segmentation would provide high value in terms of reduced customer outages. As a result of the range of risk assessments conducted, the following components and activities were identified to increase system resilience to storm events:

- Long-term planning and capacity building for adaptation
  - Develop capacity for long-term energy and climate adaptation planning
  - Enhance the collection of meteorological and hydrological data
  - Design and implement an Emergency Response and Recovery Plan at BEL
  - Enhance BEL's systems operation and management capabilities
  - Improve BEL's communication network
  - Improve BEL's vegetation management strategy

- Measures to enhance resilience of the transmission and distribution network
  - Segment the transmission network
  - Strengthen transmission network structures
  - Implement measures to enhance resilience of distribution substations

Conclusions and Key Opportunities

Belize ERCAP demonstrates the ability of climate change risk assessment to systematically identify key climate change hazards and impacts, critical points of system vulnerability, and effective adaptation measures to enhance system resilience. This case study highlights how this style of hierarchical, progressively more detailed climate risk assessment and management undertaken across the project cycle can lead to the significant and quantifiable reductions in the risk of power system failures through the identification of relevant adaptation measures.

The "Three Steps" of establishing climate adaptation co-benefits—is central to the project objectives. While this project may differ in some ways from a typical World Bank Energy sector project, it is presented here as an example of a well-conducted climate risk assessment and management process. The climate change adaptation context, intent, and linkage are reflected in the project appraisal documents:

- Context: Belize is exposed to current and future risk from tropical cyclones, with significant potential impacts on the power system.
- Intent: The project will consist of a set of adaptation measures that reduce the risks identified in historical and hypothetical analysis.
- Linkage: The project includes adaptation measures that specifically address the priority vulnerabilities identified in the risk assessment.

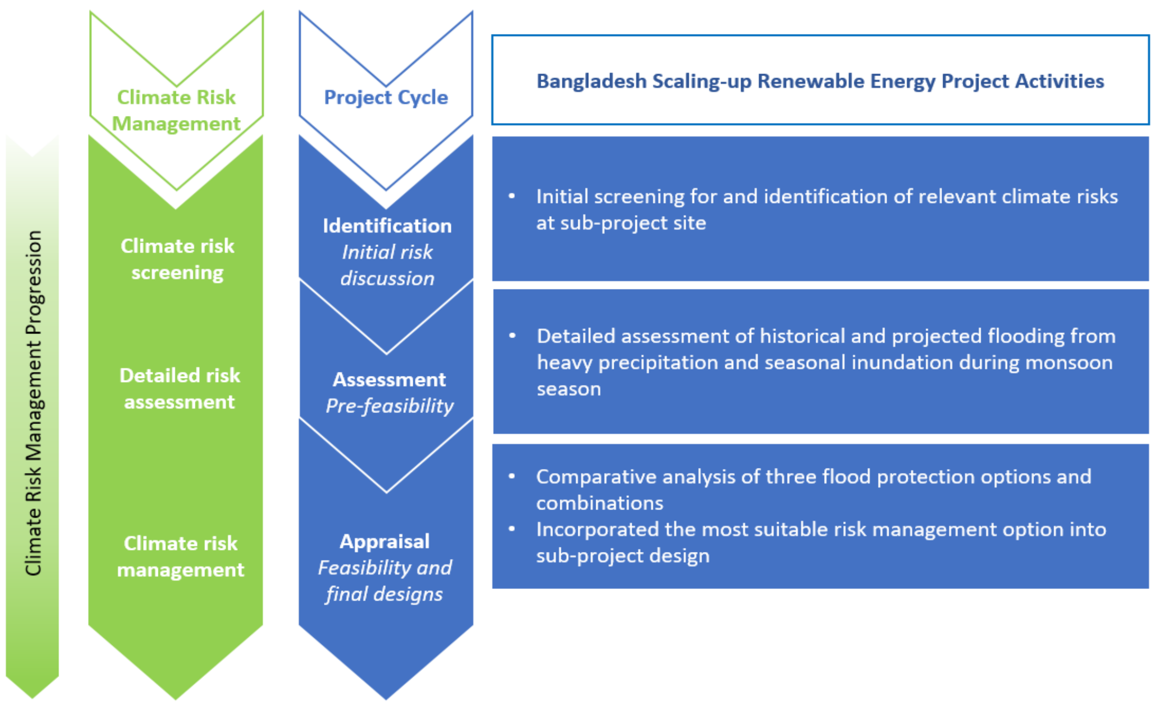
Bangladesh Scaling-up Renewable Energy Project

Background

The World Bank's Bangladesh Scaling-up Renewable Energy Project[53] incorporated climate resilience into the development of power generation infrastructure. The project objective is to increase installed generation capacity of renewable energy in Bangladesh and mobilize financing. The Project's three components are: 1) development of a 50 MW pilot phase of a renewable energy park in the Feni District; 2) establishment a dedicated Renewable Energy Financing Facility; and 3) technical assistance to scale up renewable energy – costing a total of US$413 million. The Feni pilot will be the first large-scale grid-tied solar PV system in Bangladesh, and the Task Team was motivated to ensure that the vital infrastructure sub-project is designed to be resilient to a future climate.

This case study outlines the steps that the Task Team took in conducting a climate change risk assessment and developing a risk management approach. Figure A1-2 summarizes the sequencing of climate risk assessment and management activities in various stages of the sub-project.

Figure A1-2. Bangladesh Scaling-up Renewable Energy Project Activities by Stage of Risk Management Process and Bank Project Cycle



Risk Assessment

During the Project concept stage due diligence risk screening, flood risk to the project site was identified, given that the project site is located on the floodplains of two major rivers and is adjacent to a channel that connects to the Bay of Bengal. It was determined that heavy precipitation, seasonal inundation during the monsoon, and high tides, can result in

[53] World Bank, P161869: Bangladesh Scaling-up Renewable Energy Project, 2019

flooding in the project site. [54,55] According to interviews with locals, 25% of the site is almost permanently flooded and 50% of the site is flooded given tides under present conditions. King tides impede the drainage of floodwater into the sea and increase local flooding from monsoons. Water from the Feni and Dakatiya rivers often breach the riverbanks and flood the proposed site. Locals estimated that water ingress takes place during a full moon and maximum water level is around 23-30 cm above ground within the proposed site. The maximum historical high water level was 5 m above the site level during the super-cyclone of 1991; super-cyclones of similar magnitude have occurred four times within the past 50 years. Based on that risk screening, it was determined that the ground-mounted solar sub-project is highly exposed to current and future extreme precipitation, flooding, sea level rise, and storm surge.

Detailed risk assessment

Next, the Task Team worked with consultants (Suntrace, EQMS, and WinDForce) to conduct a detailed assessment of flooding from heavy precipitation and seasonal inundation at the Feni site as part of the feasibility study. The Task Team collected daily rainfall data from the past 50 years from a nearby Bangladesh Water Development Board (BWDB) meteorological measuring station and found that the maximum daily rainfall within the last 50 years was 280 mm. Assuming this rate of rainfall occurs continuously for four days and drainage is impeded, the project site could be inundated up to 1.1 m. Additionally, the Task Team collected 50 years of historical surface water level flooding data from three BWDB measuring stations and projected future surface water levels for the next 25 years. The analysis indicated that the maximum projected surface water level from all sources of flooding including precipitation and storm surge is approximately 4 m.

Risk Management

Different options were considered for protecting the solar PV plant against floods: a) elevated PV plant, b) floating PV plant, and c) dike surrounding the PV plant. The Task Team conducted a comparative analysis of these three potential flood protection options and combinations based on the BWDB hydrological data and the cost.

Ultimately, it was determined that the combination of elevated structures for the PV panels, a dike, and water pumping for drainage inside the dike is the most suitable option for the site. Given that the maximum potential water inundation level within the project site from precipitation is estimated at 1.1 m and the maximum projected surface water level is 4 m, the solar panels will be elevated at 1.5 m and the dike built to 5 m to mitigate the flood risks. The expected cost for this elevation and dike combination is considered most moderate compared to the options of elevating the PV plant 5 m high or designing a floating PV plant.

Conclusions and Key Opportunities

By recognizing the climate risks during the initial concept phase, the Task Team was prepared to conduct a more thorough analysis of climate risks and incorporate resilience measures during the project design. While the primary objective of this project was to develop infrastructure for power production, climate resilience is a clear co-benefit. The climate change adaptation context, intent, and linkage is reflected in the project appraisal documents.

- *Context:* The sub-project site is exposed to current and projected flooding from heavy precipitation and seasonal inundation.
- *Intent*: The sub-project is to be carefully designed to mitigate the potential flooding risks identified in the detailed assessment.
- *Linkage*: The PV plant is designed at a higher elevation, with a surrounding dike, and with drainage pumps.

[54] Ahammed, Faisal & Hewa, G & R. Argue, John. 2014. Variability of annual daily maximum rainfall of Dhaka, Bangladesh. Atmospheric Research. 137. 176–182. 10.1016/j.atmosres.2013.10.013.
[55] Bangladesh Water Development Board's (BWDB) annual 2012 to 2014 flood reports on historical annual and monthly maximum rainfall.

Building Climate Resilience into Power System Investments in Bangladesh

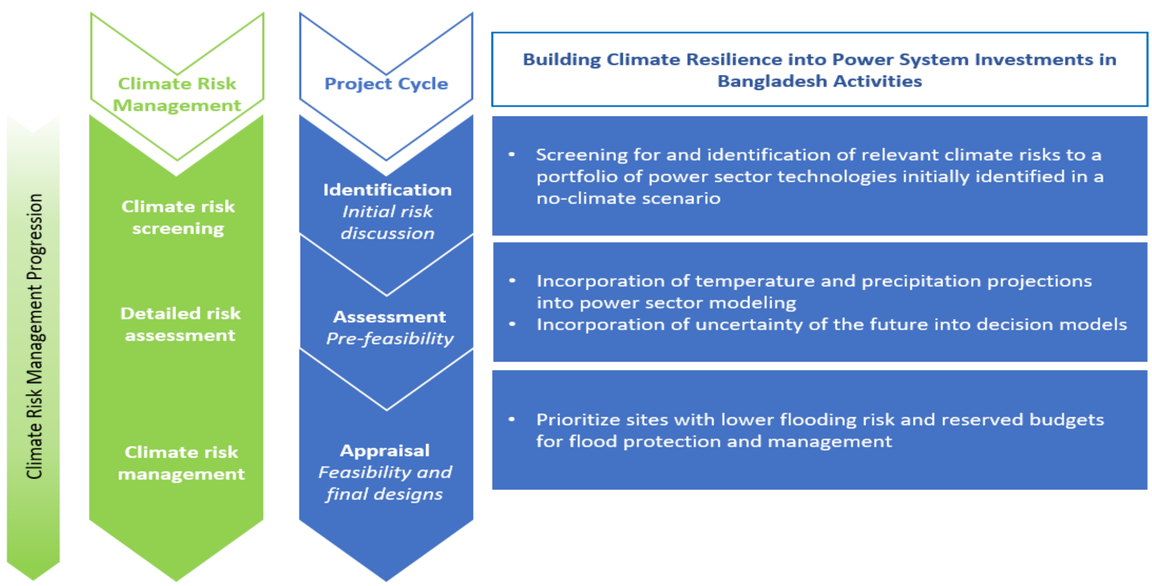
Background

Consideration of climate risks and uncertainties within power system master plans offers the opportunity to make investment decisions that perform better under a wide range of different but plausible futures. However, Bangladesh's 2016 power system master plan[56] and its least-cost planning methodology with a planning horizon to 2041 does not consider climate risks, uncertainty, and climate risk management measures. To address the need, a collaborative project[57] between the World Bank and John Hopkins University completed in 2017 sought to demonstrate an approach to cost-effectively enhance the long-term resilience of the power system by incorporating climate change into master planning.

Using the 2017 study's analysis framework, this hypothetical case study outlines the potential steps that a Task Team could take in conducting a climate risk assessment and developing a climate risk management approach in power sector investments. This hypothetical project intends to build thermal generation capacity in Bangladesh within the next 10 years in alignment with the country's power sector master plan. Figure A1-3 summarizes the sequencing of climate risk assessment and management activities in various stages of the project.

Risk Assessment

Figure A1-3. Building Climate Resilience into Power System Investments in Bangladesh by Stage of Risk Management Process and Bank Project Cycle



Climate risk screening

The World Bank and Government of Bangladesh identified a portfolio of thermal generation resources as a potential project investment, based on the resource investment plan outlined in the 2016 Power System Master Plan. During the project concept phase, a climate risk screening was undertaken. Based on a literature review and application of the

[56] JICA and TEPCO (Japan International Cooperation Agency and Tokyo Electric Power Company). 2016. Power System Master Plan 2016. Power Division, Ministry of Power, Energy, and Mineral Resources, Government of Bangladesh, Dacca.

[57] World Bank. 2017. Building Climate Resilience into Power System Planning: The Case of Bangladesh. Report No: ACS23320.

World Bank Climate Knowledge Portal's Climate Analysis Tool for Bangladesh,[58] several climate change potential impacts were identified, including:

- Impacts of flood profile changes on project investment costs (costs to protect a power plant against a flooding event of a specified return period), fixed operating costs (including insurance), and plant availability (forced outage rate).
- Impacts of temperature extremes and increases of cooling degree days on electricity demand and thermal generation capacity and efficiency.

Climate uncertainties were characterized that would affect project investments over their expected life spans, including uncertainties found in: global circulation model outputs, processing of projections for finer spatial granularity or for application to power system planning, and functions describing the impact of climate variables on the power system.

Detailed risk assessment

Given these climate risks and uncertainties, a detailed climate risk assessment was undertaken to assess potential climate impacts to the portfolio of investments. The detailed risk assessment sought to answer questions such as: How vulnerable are different power system investment strategies to flooding? How will rising temperatures affect thermal generation capacity and efficiency and electricity demand?

An 'enhanced' least-cost power system planning model was developed which incorporated potential climate impacts. For example, stressor-impact functions between the climate variables (temperature and precipitation) and power system component technical and economic performance were established. For temperature projections, the Climate Analysis Tool was used to access downscaled climate projections for Bangladesh and subnational regions which were derived from models used in the 5th Assessment Report of the Intergovernmental Panel on Climate Change. The analysis assumed percentage capacity deratings for coal, combined cycle gas turbine, and peaking open cycle gas turbine for every 1°C above 27°C. The impact of increased cooling degree days[59] on electricity demand was captured through empirical relationships based on the literature. Flood profiles for Bangladesh were provided by a flood risk modeling company (Fathom), which took potential changes in precipitation into account.[60] Where inundation depth was higher than the facility's protection level, two consequences were modeled – outage and damage to the facility.

Risk Management

In order to incorporate climate uncertainty into the power planning model, the Task Team utilized two uncertainty-based planning approaches identified in the literature:

- *Stochastic linear programming (SLP)* – determines how investment strategies perform over time given a select set of future projections.
- *Robust decision making (RDM)* – assesses the robustness of different investment strategies under a broad range of potential climate futures.

A combination of a range of plausible scenarios for future temperature, flooding, demand growth, fuel price, domestic coal supply, and natural gas supply were used to create scenarios to run through the model. Using the hybrid-SLP approach, the least-cost planning model remains the same but the decision space expands to include several scenarios,

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[58] Bangladesh Climate Change Resilience Fund. n.d. "Climate Change Knowledge Portal, Climate Analysis Tool." World Bank Group and International Center for Tropical Agriculture. http://climatewizard.ciat.cgiar.org/wbclimateanalysistool/.
[59] The Climate Analysis Tool defines cooling degree days as the number of days above 18°C.
[60] Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae. 2013. Global Flood Risk under Climate Change. Nature Climate Change 3 (9): 816–21. http://doi.org/10.1038/nclimate1911.

whose costs may be weighed against one another. Using the RDM approach, the standard least-cost planning model is implemented iteratively across all future scenarios, with some of the decisions fixed to test the performance of various investment portfolios, including generation facilities built to future flooding standards.

To evaluate performance of the proposed project investment against alternative investments of various energy and capacity mixes, the analysis used the regret metric, defined as the cost of a given strategy minus the cost of the best-performing strategy under the same case. The analysis identifies lowest regret strategies across all scenarios of plausible future conditions. The analysis found that a “climate-aware” portfolio that considers impacts from flooding and extreme temperature was more cost-efficient in terms of avoided losses compared to a no-climate portfolio.

Based on the detailed climate risk assessment and the analysis of benefits, several adjustments were made to the project. Sites with lower flooding risk were prioritized for investment and incorporated flood risk management measures, compared to the sites and designs in the base case investment portfolio. In addition, resources for flood protection measures were incorporated into the budget; additional cost components included construction to a higher flood protection standard and flood insurance. Additionally, the budget accounted for increased operational expenses due to additional load, higher derating, or outages.

Conclusion and Insights

This hypothetical project demonstrates an approach to consider a portfolio of investments based on explicitly integrating climate risks into a traditional integrated power system planning model. First, planners should identify key climate change risks to investments in the power system. Then, traditional power system planning models can be enhanced with functional relationships between climate-related variables and planning parameters to stress test different investment strategies under climate change. Additionally, this project pilots two methods to incorporate uncertainty into decision models. This approach for a progressively more detailed climate risk assessment helps understand climate risks and uncertainties that could be incorporated into long-term power sector investment decisions in Bangladesh. Considering climate change projections in power sector investments has two primary benefits: more accurate estimated costs and more cost-efficient investment decisions that lead to lower-cost power system plans. The climate change adaptation context, intent, and linkage is reflected in the hypothetical project appraisal documents:

- *Context:* Investment to expand generation capacity of a power system that is increasingly vulnerable to climate events.
- *Intent:* The project is designed to incorporate future climate risks and uncertainty.
- *Linkage:* The project portfolio of climate-resilient, cost-efficient investments in power generation prioritizes sites with lower flood risk and invests in flood protection.

Temane Regional Electricity Project

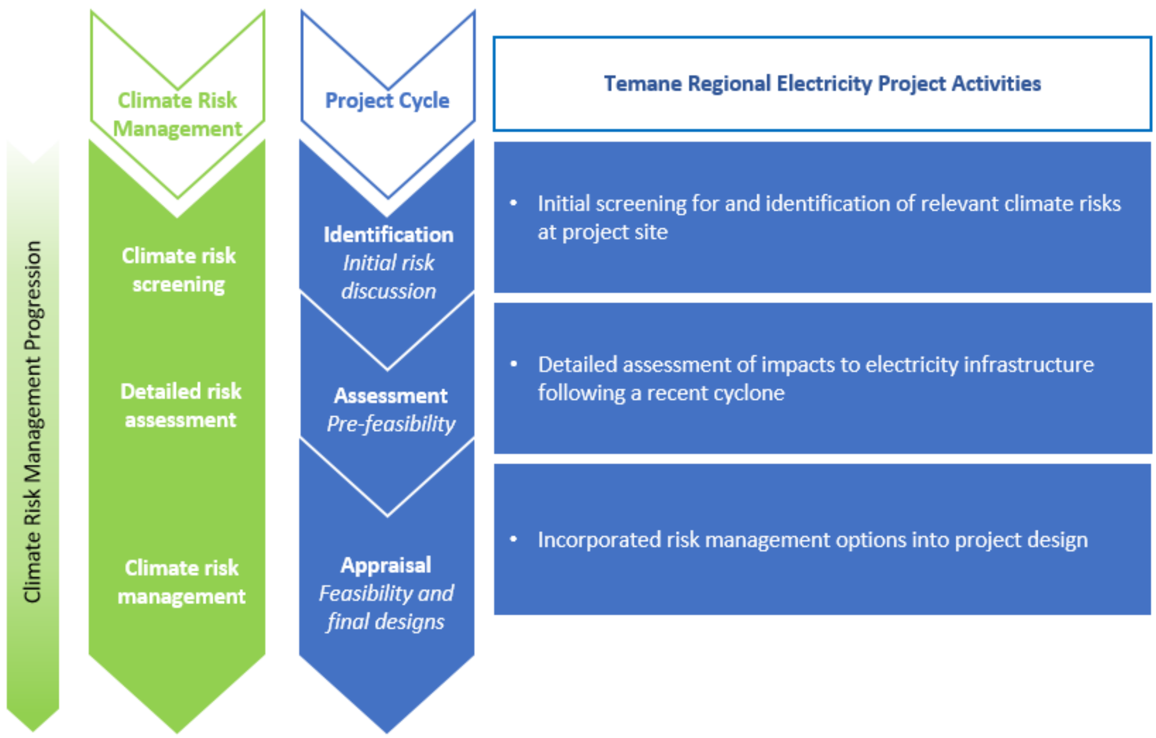
Background

The project development objective of the World Bank's Temane Regional Electricity Project[61] in Mozambique is to enhance transmission capacity for domestic and regional markets and to increase electricity generation capacity. Project components include: 1) construction of approximately 560 km of a power transmission line between Maputo and Vilanculos, and upgrading and construction of substations; 2) financing and construction of a 400 MW gas-to-power generation plant in Temane; and 3) implementation support, technical assistance, and capacity building. The Task Team incorporated resilience measures for extreme weather conditions, including wind and flooding, into the design of the infrastructure Project components.

This case study outlines the steps that the Task Team took in conducting a climate change risk screening, assessment, and risk management approach, as summarized in Figure A1-4.

Risk Assessment

Figure A1-4: Temane Regional Electricity Project Activities by Stage of Risk Management Process and Bank Project Cycle



Climate risk screening

During the Project concept stage, the Task Team screened for both recent extreme weather and projected climate change risks in Mozambique using resources including the country's Intended Nationally Determined Contribution[62] and the World Bank Climate Change Knowledge Portal.[63]

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[61] World Bank, P160427: Temane Regional Electricity Project, 2019

[62] Government of Mozambique. 2015. Intended Nationally Determined Contribution of Mozambique to the UNFCCC. https://www4.unfccc.int/sites/submissions/INDC/Published%20Documents/Mozambique/1/MOZ_INDC_Final_Version.pdf

[63] World Bank. N.d. Climate Change Knowledge Portal: Mozambique. https://climateknowledgeportal.worldbank.org/country/mozambique

The country already experiences high levels of climate variability and extreme weather events. In the south, persistent drought periods have been coupled with episodic floods. Most recently, Cyclone Idai in March 2019 made landfall in the central region near Beira. The Category 2 storm brought sustained winds of 46 meters per second along the coast, produced a storm surge of 4.4 meters in the city, and brought heavy rainfall throughout the region. Major floods severely damaged electricity infrastructure in the region.

The Task Team also recognized that Mozambique will face increased intensity of extreme weather events under a changing climate. The proportion of days with heavy rainfall events[64] has already increased by 2.6% per decade or an estimated 25 days per year between 1960 and 2006; the number of heavy rainfall events is projected to increase by 2060, particularly during the dry season (January-June).

From the initial review of relevant climate change hazards, the Task Team identified the transmission component of the Project as highly exposed. The sheer geographic distance of 560 km of transmission line increases the likelihood of winds, floods, and cyclones affecting a portion of the line. For the power plant component of the Project, the Task Team's screening confirmed that the site is not vulnerable to flooding, sea level rise, or storm surge. The proposed power plant site in Temane is approximately 20 km inland from the coastline and about 30 m above mean sea level.

Detailed risk assessment

In order to identify specific potential impacts of wind and flooding to the proposed transmission line and power plant, the Task Team reviewed a detailed assessment of Cyclone Idai impacts on the electricity sector. Recent historical impacts from extreme weather events serve as useful indicators for future impacts.

Electricity of Mozambique (EDM) – the state-owned, vertically integrated utility – hired a consultant to assess power infrastructure damages from the Cyclone. The assessment team conducted field observations and worked closely with the local EDM offices to draw on their knowledge of local conditions.

The assessment documented specific observed impacts to the electricity network from extreme weather, such as: foundation uprooting and collapse of transmission towers from strong winds; damage on conductor lines from debris carried by winds; submerged substations; and corrosion of temporarily inundated transmission towers. Damages disrupted electricity supply to an estimated 570,000 customers and the cost of physical damage to the electricity infrastructure is estimated at US$130 million.

Risk Management

To mitigate against these potential impacts and risks, the Task Team incorporated resilience measures into the transmission component of the Project, including: use of self-supporting transmission towers instead of guyed V-towers in certain sections of the line; raising platforms for new substations by 1 to 2 meters; strengthening foundations; and designing transmission lines to withstand wind loads of 40m/s and hurricane winds of 65m/s. The incremental cost of the resilience measures is approximately 20% based on technical assessment of various technology options for resilience to winds and cyclones.[65]

The Task Team also incorporated wind resilience measures into the design of the power plant, including: designing plant buildings, stacks, and towers to withstand higher wind speed; ensuring that all plant components are properly anchored

[64] Defined in the CCKP as a daily rainfall total which exceeds the threshold that is exceeded on 5% of rainy days in the current climate of that region or season.

[65] Miyamoto International. 2019. Increasing Infrastructure Resilience Background Report. World Bank Group. #7189546 Overview of Engineering Options for Increasing Infrastructure Resilience. Available at: http://documents.worldbank.org/curated/en/620731560526509220/pdf/Technical-Annex.pdf

using wind-rated mechanical attachments; properly anchoring roofs to columns and walls; and providing bracing for cooling towers. The incremental cost is estimated at approximately 10%.[66]

Conclusion and Insights

By recognizing the climate risks during the initial concept phase, the Task Team was motivated to incorporate resilience measures during the Project design. While the primary objective of this Project was to develop transmission, substation, and power plant infrastructure, climate resilience is a clear co-benefit. The climate change adaptation context, intent, and linkage is reflected in the project appraisal documents.

- *Context:* The Project is exposed to extreme weather including wind and flooding, as seen from impacts from the recent cyclone and review of future climate projections.
- *Intent*: The Project is to be carefully designed to mitigate the potential wind and flooding impacts on the electricity sector identified in the detailed assessment.
- *Linkage*: The transmission and power plant infrastructure are designed to withstand strong winds and flooding.

[66] Miyamoto International. 2019.

Annex 2. Climate Data and Resources

Data on historical and projected climate are required for climate change assessments to the power sector. Gathering and using climate change projections requires some knowledge and understanding of the climate models and emissions scenarios, uncertainty, and types of information.

Climate Models, Emission Scenarios, and Uncertainty

Climate models are based on global patterns in the ocean and atmosphere and quantifies the Earth system's complex processes. These models could differ in grid sizes, parameters, and time scales. Climate models are run with emission scenario assumptions. Multiple emissions scenarios (e.g., high, medium, low) are used to account for uncertainty associated with the world's future development path.

Different climate models may provide different outputs. To bracket uncertainties in projections and obtain a representative picture of the range of possible climate futures, climate scientists run a range of scenarios through multiple models numerous times. A best practice is to use a broad range of models and scenarios, and use a range of values to communicate understanding of likely futures accurately. Consideration of the full range of model outputs enables project planning and development that is robust to multiple possible futures.

Global climate models (GCM) produce information at roughly 100 km resolution whereas downscaling of GCM outputs can generate climate information at resolutions as fine as 1 to 2 km. Downscaled climate data can be particularly useful near coastlines and in mountainous regions where local climate and changes in topography may have a big impact on the projections. If it is important to have finer-scale information for a project, consider using downscaled climate information. At the same time, it is important to recognize that downscaling may increase rather than decrease uncertainty, particularly in countries with poor hydro-meteorological records, in small island states, and at the local or city levels. Likewise, downscaling may increase uncertainty when simulating variations in extreme events. The techniques for downscaling can produce high-resolution information, but it is important not to confuse high resolution with greater accuracy. Downscaling can be costly, time-consuming, and dependent on data quality and availability.

Table A2-1. lists CMIP5 climate models. For more detailed information and data from specific climate models, see the European Network for Earth System modelling portal.

Table A2-1. CMIP5 Climate Models

Model	Center	Institution
ACCESS1.0 **ACCESS1.3**	CSIRO-BOM	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
BCC-CSM1.1 **BCC-CSM1.1(m)**	BCC	Beijing Climate Center, China Meteorological Administration
BNU-ESM	GCESS	College of Global Change and Earth System Science, Beijing Normal University
CanAM4 **CanCM4** **CanESM2**	CCCma	Canadian Centre for Climate Modelling and Analysis

Model	Center	Institution
CCSM4 **CESM1(BGC)** **CESM1(CAM5)** **CESM1(CAM5.1,FV2)** **CESM1(FASTCHEM)** CESM1(WACCM)	NSF-DOE-NCAR	National Science Foundation, Department of Energy, National Center for Atmospheric Research
CMCC-CESM **CMCC-CM** **CMCC-CMS**	CMCC	Euro-Mediterranean Center on Climate Change
CNRM-CM5 **CNRM-CM5-2**	CNRM-CERFACS	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique
CSIRO-Mk3.6.0 **CSIRO-Mk3L-1-2**	CSIRO-QCCCE	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence
EC-EARTH	ICHEC	Irish Centre for High-End Computing
FIO-ESM	FIO	The First Institute of Oceanography
FGOALS-g2	LASG-CESS	Institute of Atmospheric Physics (LASG) and Centre for Earth System Science (CESS)
FGOALS-gl **FGOALS-s2**	LASG-IAP	Institute of Atmospheric Physics, Chinese Academy of Sciences
GEOS-5	NASA-GMAO	NASA Global Modeling & Assimilation Office
GFDL-CM2.1 **GFDL-CM3** **GFDL-ESM2G** **GFDL-ESM2M** **GFDL-HIRAM-C180** **GFDL-HIRAM-C360**	NOAA GFDL	Geophysical Fluid Dynamics Laboratory
GISS-E2-H **GISS-E2-H-CC** **GISS-E2-R** **GISS-E2-R-CC**	NASA GISS	NASA Goddard Institute for Space Studies
HadGEM2-AO	NIMR/KMA	National Institute of Meteorological Research/Korea Meteorological Administration
HadCM3 **HadGEM2-A** **HadGEM2-CC** **HadGEM2-ES**	MOHC	Met Office Hadley Centre
INM-CM4	INM	Institute for Numerical Mathematics

Model	Center	Institution
IPSL-CM5A-LR **IPSL-CM5A-MR** **IPSL-CM5B-LR**	IPSL	The Institute Pierre Simon Laplace
MIROC-ESM **MIROC-ESM-CHEM** **MIROC4h** MIROC5	MIROC	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MPI-ESM-LR **MPI-ESM-MR** **MPI-ESM-P**	MPI-M	Max Planck Institute for Meteorology
MRI-AGCM3-2H **MRI-AGCM3-2S** MRI-CGCM3 MRI-ESM1	MRI	Meteorological Research Institute
NorESM1-M **NorESM1-ME**	NCC	Norwegian Climate Centre

Climate Indices and Data Resources

Climate information includes variables (e.g., temperature and precipitation) that should be used to inform climate change assessments to the power sector. Table A2-2. provides example climate indices relevant for energy infrastructure and related climate impacts. Table A2-3. provides a curated list of resources that provide climate data and indices. Where available, local meteorological data should be prioritized.

Current and historical climate information can be used to assess the extent to which exposure to climate hazards has previously caused impacts to the power sector, and establish a baseline against which future exposure and impacts can be compared. Future climate change projections can be used to explore possible future climatic conditions given different scenarios of change, at different points of time in the future. A good starting point for gathering relevant climate information is to consider which climate hazards have affected the power infrastructure and demand in the past.

Table A2-2. Illustrative Climate Indices Relevant to the Power Sector

Climate Hazard	Illustrative Climate Indices	Relationship to Power Sector
Temperature	- Average temperature - Average daily maximum/minimum temperature - Cooling/heating degree days	- Solar power cell and battery efficiency - Wind power generation efficiency - Thermal gradient and geothermal generation efficiency - Natural gas-fired combustion turbine efficiency - Evapotranspiration of reservoirs and watersheds for hydropower supply - Substation capacity and transformer lifespan

Climate Hazard	Illustrative Climate Indices	Relationship to Power Sector
		- Transmission and distribution efficiency and line sag - Cooling and heating demand
Precipitation	- Average precipitation - Precipitation amount during wettest days - Maximum number of consecutive wet/dry days	- Supply of cooling water - Shifts in peak flow and peak generation for hydropower
Sea Level Rise	- Sea level rise extent - Coastal flooding extent	- Inundation of power infrastructure and reduced infrastructure lifespan - Salt water corrosion of electrical components
Extreme Heat	- Number of hot days (e.g., maximum temperature >25°C) - Number of hot nights (e.g., minimum temperature >20°C) - Days with heat index >35°C - Warm Spell Duration Index	- Solar power cell and battery efficiency - Wind power generation efficiency - Thermal gradient and geothermal generation efficiency - Transmission and distribution efficiency and line sag - Cooling demand
Drought	- Average precipitation - Maximum number of consecutive dry days - Annual SPEI drought index	- Supply of cooling water - Solar power cell efficiency - Shifts in peak flow and peak generation for hydropower - Evapotranspiration of reservoirs and watersheds for hydropower supply
Wildfire	- Number of hot days (e.g., maximum temperature >25°C) - Maximum number of consecutive dry days	- Physical damage to power infrastructure - Transmission capacity
Extreme Precipitation / Riverine Flooding	- Average largest 1-day precipitation - Average largest 5-day cumulative rainfall - Precipitation amount during wettest days	- Physical damage to power infrastructure - Supply of cooling water - Solar panel delamination - Shifts in peak flow and peak generation for hydropower - Sediment concentration in reservoir water

Climate Hazard	Illustrative Climate Indices	Relationship to Power Sector
	- 10-year return level of 5-day precipitation - 10-year return level of monthly precipitation - Days with precipitation >20mm - Maximum number of consecutive wet days - Flooding extent from 1-percent annual exceedance probability event	
Coastal Storms / Flooding / Winds	- Wind speed - Number of days with low wind speed - Coastal flooding extent	- Physical damage to power infrastructure - Salt water corrosion of electrical components - Solar power cell efficiency - Wind power generation efficiency - Transmission efficiency
Icing and Cold Weather Outbreaks	- Average daily minimum temperature - Heating degree days - Cold Spell Duration Index - Number of frost days (e.g., minimum temperature <0°C)	- Physical damage to power infrastructure - Transmission efficiency and capacity - Heating demand

Table A2-3. Resources for Historical Climate Information and Future Projections[67]

Information Type	Source	Format	Brief Description
Requires little prior experience to find relevant climate information			
Temperature and precipitation	**World Bank Climate Change Knowledge**	Map interface with links to	The Climate Change Knowledge Portal provides historical temperature and precipitation data, and projected global and downscaled CMIP5 climate model data from several climate models and for several greenhouse gas emission scenarios.

[67] Modified from U.S. Agency for International Development, 2017. "Using Climate Information for Climate Risk Management."
https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID_Primer-Using-Climate-Info-for-CRM.pdf

Information Type	Source	Format	Brief Description
data and projections	Portal and Interactive Climate Indicator Dashboard for Energy	data and graphics	The Climate Change Knowledge Portal's Climate Indicator Dashboard for Energy provides projected climate indices relevant to energy sub-sectors: oil, gas and coal mining; thermal power generation; hydropower; other renewable energy; energy efficiency in heat and power and end use; and transmission and distribution of electricity.
Temperature and precipitation data and projections	UNDP Climate Change Country Profiles	Web page summary with links to reports and observed and modeled data	The UNDP provides historical and projected CMIP3 temperature and precipitation data relevant to the power sector for 52 countries. The profiles include brief narratives as well as data tables, graphs, and maps, which summarize and illustrate the trends and projections. The web page also provides a link to documentation regarding the data included in the profiles.
Tropical cyclones	NOAA Historical Hurricane Tracks	Searchable map interface with filters	The National Oceanic and Atmospheric Administration (NOAA) provides historical track information on tropical cyclones. This information may be useful for assessing tropical cyclone risk to energy infrastructure.
Coastal flooding data	Climate Central Surging Seas	Visualization tool	Graphical interface provides visualizations of projected coastal flooding extent; provides links to similar tools for river floods, droughts, and other climate hazards
Sea level trends	NOAA Sea Level Trends	Map interface with trend data in summary and graph form	The US National Oceanic and Atmospheric Administration (NOAA) provides historical information on sea level trends in an easy-to-use map interface that provides quick links to underlying data for select coastal cities globally. Although this site is now a bit dated (2013), it is included here because of ease of use.
Requires advanced experience to find relevant climate information			
Temperature and precipitation data	ClimDex	Web page with links to datasets and software	ClimDex provides historical data on temperature and precipitation extremes in the form of indices relevant to the power sector. However, the interface requires some familiarity with using large datasets and its main purpose is to facilitate research.
Drought and flood data	WMO and Global Water Partnership Integrated Drought Management Programme	Searchable, sortable web database with links to drought indices	The Integrated Drought Management Program provides a wide array of historical global drought and flood information resources including indicators and indices for specific contexts and applications. Some searching is needed to obtain information you may want.

Information Type	Source	Format	Brief Description
Climate and land surface data and analytical services for decision support	**SERVIR**	Web portal with access to imagery, data, tools, products and maps	SERVIR, a joint program of National Aeronautics and Space Administration (NASA) and United States Agency for International Development (USAID), provides remotely sensed data for a range of historical climate and land surface variables as well as products and services requested by target countries and partners. The analytical services provide decision support for sectors include water resources, which may be applied to hydropower. To access relevant information from the main site, select 'data and maps'.
Climate data	**KNMI Climate Explorer**	Tool for statistical analysis	This web application provides an interface for visualization and statistical analysis of historical and projected CMIP5 climate data. It is mainly for research purposes; experience using models and understanding of climate variables are needed to obtain useful information from the tool. The Climatic Research Unit of the University of East Anglia and NASA's Goddard Institute for Space Studies provide similar data and tools.
Climate data	**Columbia University's Climate Data Library**	Portal with links to data and maps	Columbia's International Research Institute Climate Data Library contains hundreds of historical climate-related datasets. Experience using models and understanding of climate variables are needed to obtain useful information from the library.

Annex 3. Resources for Climate Impacts to Power Sector Components

Power sector assets and services are vulnerable to both chronic and acute climate hazards, which impact power generation (e.g., derating/degradation of thermal generation capacity), transmission and distribution (e.g., transfer capability), as well as power demand. Table A3-1. lists resources that provide information on potential physical and performance related climate risks to power infrastructure, characterized by power component and climate hazard.

Table A3-1. Resources on Climate Risks to Power Infrastructure

Resource	Power Component			Climate Hazard(*s*)
	Generation	*Transmission*	*Distribution*	
The Asian Development Bank's Report: Climate Risk and Adaptation in the Electric Power Sector (2012)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
The Asian Development Bank's Report: Guidelines for Climate Proofing Investment in the Energy Sector (2013)	Solar, Wind, Geothermal, Gas, Hydropower	Lines/ Towers	Transformers, Lines/ Poles	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
CIGRE's Report: Air Insulated Substation Design for Severe Climate Conditions (2015)			Substation	Extreme Heat, Extreme Precipitation/ Riverine Flooding, Icing and Cold Weather Outbreaks
Energy Sector Management Assistance Program's Hands-on Energy Adaptation Toolkit (2010)	General	General	General	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Wildfire, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
USAID's Climate Risk Screening and Management Tools for Strategy, Project, and Activity Designs: Annex for Construction and Energy (2017)	Solar, Wind, Geothermal, Gas, Hydropower			Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
USAID's Factsheet: Addressing Climate Change Impacts on Infrastructure: Preparing for Change - Energy Systems (2012)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
USAID's Framework: Screening Hydropower Facilities for Climate Change Risks to Business Performance (2017)	Hydropower			Temperature, Precipitation, Drought, Extreme Precipitation/ Riverine Flooding
U.S. DOE's Report: Climate Change and the Electricity Sector: Guide for Assessing Vulnerabilities and Developing Resilience Solutions to Sea Level Rise (2016)	General	Lines/ Towers	Substations, Lines/ Poles	Sea level rise, Coastal Storms/ Storm Surge/ Winds

Resource	Power Component			Climate Hazard(s)
	Generation	*Transmission*	*Distribution*	
U.S. DOE's Report: Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions (2015)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Wildfire, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
U.S. DOE's Report: Hardening and Resiliency: U.S. Energy Industry Response to Recent Hurricane Seasons (2010)	Gas	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Coastal storms/ Storm Surge/ Winds
U.S. DOE's Report: U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather (2013)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Sea Level Rise, Extreme Precipitation/ Riverine Flooding, Drought, Coastal Storms/ Storm Surge/ Winds
U.S. GAO's Report: Climate Change Energy Infrastructure Risks and Adaptation Efforts (2014)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Wildfire, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds
Working Group II's contribution to the IPCC's Fifth Assessment Report: Key Economic Sectors and Services, Chapter 10 (2014)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Extreme Precipitation/ Riverine Flooding, Drought, Coastal Storms/ Storm Surge/ Winds
The World Bank's Climate and Disaster Risk Screening Tool (2015)	Solar, Wind, Geothermal, Gas, Hydropower	General	General	Temperature, Sea Level Rise, Extreme Precipitation/ Riverine Flooding, Drought, Coastal Storms/ Storm Surge/ Winds
The World Bank's Report: Climate Impacts of Energy Systems: Key Issues for Energy Sector Adaptation (2011)	Solar, Wind, Geothermal, Gas, Hydropower	Substations, Lines/ Towers	Substations, Transformers, Lines/ Poles	Temperature, Precipitation, Sea Level Rise, Extreme Heat, Drought, Extreme Precipitation/ Riverine Flooding, Coastal Storms/ Storm Surge/ Winds

Table A3-2. Resources on Fragility and Damage Curves for Power Infrastructure

Power Asset	Hazard (Metric)	Fragility and Damage Curve Details[68]
Thermal Power Plant: Buildings, Structures, and Stacks	Wind (m/sec)	Wind gust at 10m and probability of exceeding a damage state
Substation	Wind (km/hr)	Wind speed and probability of failure
Substation	Flood (ft)	Flood depth and percent damage
Transmission and Distribution Towers	Wind (km/hr)	Wind speed and probability of failure
Overhead Transmission and Distrbution Systems	Flood (ft)	Flood depth and percent damage

[68] Miyamoto International. 2019. Increasing Infrastructure Resilience Background Report. World Bank Group. #7189546 Overview of Engineering Options for Increasing Infrastructure Resilience. Available at: http://documents.worldbank.org/curated/en/620731560526509220/pdf/Technical-Annex.pdf

Annex 4. Details on Adaptation Measures

A range of adaptation measures can be implemented to address climate impacts across the power sector, including for generation, transmission and distribution assets. A variety of different types of measures are described, including structural, policy and planning, land use, or operational initiatives. Table A4-1.,

Table A4-2., and

Table A4-3. provide details on potential adaptation measures for each asset component, as well as cross cutting measures that can appy across components. The tables also list the climate hazards and impacts that are addressed by each adaptation measure, as well as associated cost estimates where available.

Table A4-1. Adaptation Measures for Power Generation

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Solar	Temperature increases	Leverage pole-top designs that improve passive airflow beneath photovoltaic mounting structures, reducing panel temperature and increasing power output	Power efficiency and output reductions	Structural	Module racking costs estimated to be 3 – 4 times more expensive than ground mount racking[69]
Solar	Temperature increases	Install more heat-resistant photovoltaic models such as crystalline silicon cells, and module materials designed to better withstand opeating conditions in extreme heat	Power efficiency and output reductions	Structural	\$0.8 - \$1.3/W-DC[70]
Solar	Cloud cover increases	Site solar photovoltaic systems where expected changes in cloud cover are relatively low	Power efficiency and output reductions	Land Use Planning	
Solar	Coastal storms, Winds and Extreme Precipitation	Invest in improved weather prediction systems to improve reliability of expected panel output by removing critical equipment reinstalling after adverse weather conditions pass	Generation infrastructure damage	Operational	Estimated labor installation costs range from \$0.14/W-DC to \$0.48/W-DC[71]
Solar	Drought and Winds	Invest in washing procedures to remove dust and clean panels to increase output and avoid related damages including hotspots	Generation infrastructure damage	Operational	\$0.80-\$1.30/kW-yr for an annual cleaning. For more frequent and optimized washing schedules, cost can

[69] Northern Arizona Wind & Sun. 2019. Tamarack TP/06LL Universal Top of Pole Mount. Available at: https://www.solar-electric.com/uni-tp-06ll.html?gclid=CMGWl83W1eICFZiLyAodnAQL1g

[70] Bolinger, M. and J. Seel. 2018. Utility-Scale Solar Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States - 2018 Edition. Published by Lawrence Berkeley National Laboratory.

[71] Bolinger and Seel, 2018

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
					be closer to $20/kW-year[72,73]
Solar	Temperature increases	Expand network capacity to ensure reliability	Power efficiency and output reductions	Structural	Example costs could range from $285,000/mile to $390,000/mile depending on the network capacity upgrade[74]
Solar	Cloud cover increases	Store electrical energy in battery banks to allow a greater percentage of solar energy into the grid during periods of low output	Power efficiency and output reductions	Structural	$400 to $800 per kWh per battery
Solar	Wind	Install proper anchorage support for platform to manage higher wind loads	Generation infrastructure damage	Structural	More robust design leads to ~15% higher cost[75]
Solar	Flood	Ensure that support columns have adequate strength and embedment to mitigate loss of soil due to scour; increase the size of footings; use riprap	Generation infrastructure damage	Structural	
Wind	Wind pattern changes	Install larger turbines and taller structures/towers to increase capacity factor	Power efficiency and output reductions	Structural	
Wind	Coastal storms	Construct towers using twisted jacket foundations to protect against storms and extreme winds	Generation infrastructure damage to offshore wind generation	Structural	

[72] Jones, R.K., A. Baras, A. Al Saeeri, A. Al Qahtani, A.O. Al Amoudi, Y. AL Shaya, M. Alodan, and S.A. Al-Hsaien. 2016. Optimized Cleaning Cost and Schedule Based on Observed Soiling Conditions for Photovoltaic Plants in Central Saudi Arabia. IEEE Journal of Photovoltaics 6(3):730-738. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7431986

[73] EPRI. 2015. Budgeting for Solar PV Plant Operations & Maintenance: Practices and Pricing. Published by Electric Power Research Institute. Available at: https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2016/160649r.pdf

[74] ELP. 2013. Underground vs. Overhead: Power Line Installation-Cost Comparison and Mitigation. Published by Electric Light & Power. Available at: https://www.elp.com/articles/powergrid_international/print/volume-18/issue-2/features/underground-vs-overhead-power-line-installation-cost-comparison-.html

[75] Miyamoto International. 2019. Increasing Infrastructure Resilience Background Report. World Bank Group. #7189546 Overview of Engineering Options for Increasing Infrastructure Resilience. Available at: http://documents.worldbank.org/curated/en/620731560526509220/pdf/Technical-Annex.pdf

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Wind	All	Choose sites for new installations that take into account expected changes in wind speed, storm surge, sea level rise, and river flooding during the life of the turbine	Generation infrastructure damage	Land Use Planning	
Wind	Severe weather	Invest in improved weather prediction systems to improve the turbine reliability of expected output	Generation infrastructure damage	Operational	
Wind	Wind speed increases	Store electrical energy to allow a greater percentage of wind energy into the grid during periods of low output	Power efficiency and output reductions	Structural	
Wind	Wind speed increases	Optimize blade configuration; use material with higher fatigue life; design to higher threshold than code-minimum	Generation infrastructure damage	Structural	The use of better material will add ~5% cost to the turbine design[75]
Wind	Sea level rise and storm surge	Use deep foundations	Generation infrastructure damage	Structural	Retrofitting turbines is ~30% of capital costs[75]
Geothermal	Drought	Implement dry cooling technologies in water-limited areas	Power plant reliability	Structural	
Geothermal	Drought	Equip plants with technologies that enable water reuse	Power plant reliability	Structural	
Gas	Drought	Retrofit power plants with water saving cooling techologies, including hybrid wet-dry cooling and dry cooling)	Power plant reliability	Structural	
Gas	Drought	Install equipment capable of using alternative water sources (e.g. brackish water)	Power plant reliability	Structural	
Gas	Drought	Install steam-powered chillers to reduce burden on local power system on hot days	Power plant reliability	Structural	

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Gas	Extreme heat and Drought	Prepare emergency contingency plans to ensure adequate cooling water to cope with drought and extreme temperatures and competing water demands	Power plant reliability	Policy and Planning	
Gas	Sea level rise and Storm surge	Install waterproofing measures such as concrete moat walls, floodgates and water-tight doors, sluice gates and submersible pumps	Generation infrastructure damage	Structural	
Gas	Sea level rise and Storm surge	Develop siting rules for new coastal power plants to minimize flood risk	Generation infrastructure damage	Land Use Planning	
Gas	Sea level rise and Storm surge	Perform soil improvements or use a deep foundation to prevent liquefaction risk	Generation infrastructure damage	Structural	A deep foundation could add ~20% to the construction cost[75]
Gas	Extreme Precipitation	Purchase pumps and implement water removal protocols; install flood monitoring devies	Generation infrastructure damage	Operational	
Gas	Rivervine Flooding	Construct steel sheet piles	Generation infrastructure damage	Structural	Constructing steel sheet piles is ~2% of thermal power plant cost[75]
Gas	Wind	Construct using wind-resistant attachment components (e.g., stiff braced structures helical strake)	Generation infrastructure damage	Structural	10% higher cost than traditional design[75]
Cross cutting	All	Install SCADA systems that integrate real-time weather information to improve reliability	Generation infrastructure damage	Policy and Planning	$30,000 - $120,000
Cross cutting	Sea level rise and Storm surge	Install coastal barries (e.g., seawalls, coastal vegetation and marshes) to reduce storm surge volume and inundation	Generation infrastructure damage	Structural	
Cross cutting	Sea level rise and Storm surge	Secure access to local tide gauge information to monitor water level changes	Generation infrastructure damage	Policy and Planning	

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Cross cutting	Temperature increases	Build additional generation capacity to account for heat-driven demand increases and capacity reductions	Power efficiency and output reductions	Structural	Marginal $/kw or $/MW of the dispatched generation technology
Cross cutting	Severe Weather	Incorporate climate change projections into engineering design and planning design specifications to enable structures to better withstand more extreme conditions	Generation infrastructure damage	Planning	$50,000 to $200,000
Cross cutting	Riverine flooding	Plan to locate generation infrastructure away from high risk areas (such as historic floodplains)	Generation infrastructure damage	Policy and Planning	
Cross cutting	Temperature increases	Invest in decentralized power generation such as rooftop PV generators or household geothermal units	Power efficiency and output reductions	Structural	$3.5 – $3.8/W-DC[76]
Cross cutting	Severe Weather	Ensure adequate backup generation and cooling systems for plants facing increased exposure to flooding, drought, and other extremes	Power efficiency and output reductions	Policy and Planning	
Cross cutting	Severe Weather	Develop microgrids or invest in generators to ensure backup power at critical downstream infrastructure, including hospitals, emergency services, critical utilities and disadvantaged communities	Power efficiency and output reductions	Policy and Planning	$150,000,000 for 40MW average load

[76] Barbose, G. and N. Darghouth. 2018. Tracking the Sun: Installed Price Trends for Distributed Photovoltaic Systems in the United States – 2018 Edition. Published by Lawrence Berkeley National Laboratory. Available at: https://emp.lbl.gov/sites/default/files/tracking_the_sun_2018_edition_final_0.pdf

Table A4-2. Adaptation Measures for Power Transmission

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Substation	Extreme temperatures	Build additional transmission substations and/or capacity to address increased load demand and increase resilience to efficiency losses	Transmission capacity and efficiency reductions	Structural	Transmission line costs range from $960,000/mile to $$1,600,000/mile depending on voltage and line construction.[77] Base transmission substation costs are expected to start at a minimum of $4,000,000
Substation	Extreme temperatures	Install additional levels of cooling (e.g. forced air) and heat tolerant technologies and materials	Transmission capacity and efficiency reductions	Structural	
Substation	Extreme precipitation, Sea level rise and Storm surge	Elevate control room and critical equipment to reduce flood hazard potential	Transmission infrastructure damage	Structural	>$800,000 to >$5,000,000 to elevate
Substation	Extreme precipitation, Sea level rise and Storm surge	Build levees, flood walls and moats to reduce damage from flooding and couple with pumping systems	Transmission infrastructure damage	Structural	Reinforced floodwalls ~ $200,000 per mile; new flood walls ~$4,000,000
Substation	Extreme precipitation, Sea level rise and Storm surge	Install foam waterproofing within cable conduits	Transmission infrastructure damage	Structural	
Substation	Extreme precipitation, Sea level rise and Storm surge	Elevate critical in-building components and systems above anticipated flooding levels	Transmission and substation equipment damage	Structural	
Substation	Extreme precipitation, Sea level rise	Enclose critical infrastructure components and	Transmission infrastructure damage	Structural	

[77] Black & Veatch. 2014. Capital Costs for Transmission and Substations: Updated Recommendations for WECC Transmission Expansion Planning. Available at: https://www.wecc.org/Reliability/2014_TEPPC_Transmission_CapCost_Report_B+V.pdf

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
	and Storm surge	systems in submersible casings			
Substation	Extreme precipitation, Sea level rise and Storm surge	Invest in backup generators for substation equipment	Substation power electronics equipment failure	Structural	$20,000 per substation for backup generators
Substation	Sea level Rise	Use deep foundations	Transmission and substation equipment damage	Structural	A deep foundation could add approximately 20% to the construction cost[75]
Substation	Increased wind speed	Increase robustness of elevated components	Transmission and substation equipment damage	Structural	Increasing robustness could increase cost by ~20%[75]
Lines	Wildfire, Coastal Storms, Extreme precipitation	Underground critical and high-voltage transmission lines	Transmission infrastructure damage	Structural	$500,000 to $30,000,000 per mile (more for urban areas/new construction)
Lines	Extreme heat, Coastal storm, Wildfire	Install sectionalizing switches to limit customer impacts of a fault	Reduce customer outage magnitude and frequency	Structural	$750,000 per isolation switch
Lines/Towers	Wildfire	Clear vegetation and increase fire corridors around transmission lines	Transmission infrastructure damage	Land Use Planning	
Lines	Icing	De-energizing and short-circuiting of lines to melt ice	Transmission infrastructure damage	Operations	
Lines/Towers	Icing	Strategically reinforce suspension towers such that they act as anchors and stop progression of a cascade of falling towers	Transmission infrastructure damage	Structural	
Lines/Towers	Wildfire	Design alternative transmission routes to avoid wildfire zones	Transmission infrastructure damage	Land Use Planning	

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Lines/Towers	Riverine Flooding	Design alternative transmission routes to avoid riverine flood zones (e.g., designated 100-year flood zones)	Transmission infrastructure damage	Land Use Planning	
Towers	Coastal Storms	Purchase temporary transmission towers (special design distinct from surplus transmission towers) for interim service restoration	Transmission capacity and efficiency reductions	Policy and planning	
Lines/Towers	Sea level rise and Storm surge	Construct levees, berms, floodwalls, and barriers to protect exposed transmission infrastructure	Transmission infrastructure damage	Structural	$1,500 to $2,000 per linear foot
Lines	Extreme heat	Use transmission line materials that can withstand high temperatures	Transmission capacity and efficiency reductions	Structural	Multiplier of using more effective materials expected to reach as high as 3.6[78]
Lines	Extreme heat	Build new transmission lines to reduce congestion	Transmission capacity and efficiency reductions	Structural	Transmission line costs range from $960,000/mile to $1,600,000/mile depending on voltage and line construction[79]
Lines	Extreme heat	Design to higher transmission voltages to reduce resistive losses	Transmission capacity and efficiency reductions	Structural	Approximately 1.6 times as expensive in more extreme cases[80]
Lines/Towers	Winds and Wildfire	Create vegetation buffers around exposed transmission infrastructure	Transmission infrastructure damage	Structural	$70 to $120 per linear foot
Lines/Towers	Coastal storms and wind	Install guy wires to towers and vulnerable structures	Transmission infrastructure damage	Structural	

[78] Black & Veatch, 2014
[79] Black & Veatch, 2014
[80] Black & Veatch, 2014

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Towers	Coastal storms, Storm surge, Riverine flooding, Wildfire	Reinforce or replace towers with stronger materials such as steel and concrete or additional supports to increase resilience	Transmission infrastructure damage	Structural	
Towers	Sea level rise	Use deep foundation	Equipment damage	Structural	A deep foundation could add approximately 20% to the construction cost[75]
Towers	Increased winds	Use steel, concrete or composite towers Use vibration dampers	Equipment damage	Structural	Improved design could increase cost by ~20%[75]
Lines	Storms	Use aerial bundled cables/conductors to help reduce outages	Equipment damage	Structural	Aerial bundled cables/conductors are 2-15x more expensive that overhead conductors[81]
Cross cutting	All	Develop islandable microgrids with distributed generation	Transmission capacity and efficiency reductions	Policy and Planning	$150,000,000 for 40MW average load
Cross cutting	All	Install smart metering that accelerate identification of faults and service restoration	Reduce customer outage magnitude and frequency	Policy and planning	$200 to >$300 per smart meter
Cross cutting	All	Install SCADA systems that integrate real-time weather information to improve reliability	Reduce customer outage magnitude and frequency	Policy and planning	
Cross cutting	Extreme Precipitation, Sea level rise and Drought	Invest in short-and medium-term climate and hydrologic assessments when siting and designing projects	Transmission infrastructure damage	Policy and planning	

[81] World Bank Group. 2019. Stronger Power: Improving Power Sector Resilience to Natural Hazards. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/31910/Stronger-Power-Improving-Power-Sector-Resilience-to-Natural-Hazards.pdf?sequence=1&isAllowed=y

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Cross cutting	Severe weather	Increase resources for more frequent maintenance	Transmission infrastructure damage	Operations	
Cross cutting	Temperature increases	Track changes in annual high temperatures and resulting peak load to determine need for future capacity increases	Transmission capacity and efficiency reductions	Policy and planning	
Cross cutting	Severe weather	Update aging transmission infrastruture to increase resilience against a range of climate hazards	Transmission capacity, efficiency reductions and increased risk of high customer outage magnitude and frequency	Policy and planning	>$400,000 per mile

Table A4-3. Adaptation Measures for Power Distribution

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Substation	Extreme heat	Build additional distribution substations and/or capacity to address increased load demand and increase resilience to efficiency losses	Distribution capacity and efficiency reductions	Structural	$3,000,000 to $5,000,000
Substation	Extreme heat	Install cooling and heat tolerant technologies and materials	Distribution infrastructure damage	Structural	As high as 3.6 times more than standard design materials[82]
Substation	Extreme precipitation, Sea level rise and Storm surge	Build levees, flood walls and moats to reduce damage from flooding and pair with pumping systems	Distribution infrastructure damage	Structural	Reinforced floodwalls ~ $200,000 per mile; new flood walls ~$4,000,000
Substation	Extreme precipitation, Sea level rise and Storm surge	Elevate critical in-building components and systems above anticipated flooding levels	Distribution infrastructure damage	Structural	>$800,000 to >$5,000,000 to elevate
Substation	Extreme precipitation, Sea level rise and Storm surge	Install foam waterproofing of cable conduits	Distribution infrastructure damage	Structural	
Substation	Extreme precipitation, Sea level rise and Storm surge	Invest in backup generators	Distribution capacity and efficiency reductions	Policy and planning	$20,000 per substation
Substation	Sea level Rise	Use deep foundations	Transmission and substation equipment damage	Structural	A deep foundation could add approximately 20% to the construction cost[75]
Substation	Increased wind speed	Increase robustness of elevated components	Transmission and substation equipment damage	Structural	Increasing robustness could increase cost by ~20%[75]

[82] Black & Veatch, 2014

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Transformer	Extreme heat	Upgrade transformers; install cooling systems such as forced-air or forced-oil cooling	Distribution capacity and efficiency reductions	Structural	
Transformer	Extreme heat	Remote monitoring of distribution transformer load and temperature to	Distribution capacity and efficiency reductions	Operations	$30,000 to $70,000 per transformer
Transformer	Extreme precipitation, Sea level rise and Storm surge	Enclose critical infrastructure components and systems in submersible casings	Distribution infrastructure damage	Structural	$70,000 per transformer
Lines	Wildfire, Coastal Storms, Extreme precipitation	Underground critical distribution lines	Distribution infrastructure damage	Structural	$100,000 to $8,000,000 per mile
Lines/Poles	Severe weather	Increase resources for more frequent maintenance visits	Distribution infrastructure damage	Operations	
Lines	Extreme heat, Coastal storm, Wildfire	Install sectionalizing switches to limit customer impacts of a fault	Reduce customer outage magnitude and frequency	Structural	$750,000 per isolation switch
Lines/Poles	Riverine flooding	Design alternative distribution routes to avoid riverine flood zones (e.g., designated 100-year flood zones)	Distribution capacity and efficiency reductions	Land Use Planning	
Poles	Wildfire, Sea level rise, Storm surge	Replace wooden utility poles and support structures with stronger materials (e.g., concrete or steel)	Distribution infrastructure damage	Operations	$15,000 to $40,000 per mile for wood-to-steel replacement
Poles	Severe weather	Install guy wires for poles to harden infrastructure against storms and winds	Distribution infrastructure damage	Structural	$600 to $900 per pole
Lines/Poles	Severe weather	Create vegetation buffers around exposed transmission infrastructure	Distribution infrastructure damage	Structural	$70 to $120 per linear foot

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Lines	Extreme temperatures	Use distribution line materials that can withstand high temperatures	Distribution capacity and efficiency reductions	Structural	As high as 3.6 times more than standard design materials[83]
Lines	Wildfires	Clear vegetation corridors in high wildfire risk areas	Distribution infrastructure damage	Operations	$12,000 per mile
Lines/Towers	Sea level rise	Use deep foundation	Equipment damage	Structural	A deep foundation could add approximately 20% to the construction cost[75]
Towers	Increased winds	Use steel, concrete or composite towers Use vibration dampers	Equipment damage	Structural	Improved design could increase cost by ~20%[75]
Cross cutting	All	Install smart metering that accelerate identification of faults and service restoration	Reduce customer outage magnitude and frequency	Policy and planning	$200 to >$300 per smart meter
Cross cutting	All	Install SCADA systems that integrate real-time weather information to improve reliability	Reduce customer outage magnitude and frequency	Policy and planning	$30,000 to $80,000
Cross cutting	All	Develop islandable microgrids with distributed generation	Distribution capacity and efficiency reductions	Policy and Planning	$150,000,000 for 40MW average load
Cross cutting	Severe weather	Update aging distribution infrastructure to increase resilience	Distribution capacity, efficiency reductions and reduce customer outage magnitude and frequency	Policy and Planning	
Cross cutting	Extreme Precipitation, Sea level rise and Drought	Invest in short-and medium-term climate and hydrologic assessments when siting and designing projects	Distribution infrastructure damage	Policy and Planning	

[83] Black & Veatch, 2014

Asset	Climate Hazard	Adaptation Measure	Impacts Addressed	Type	General Range or Example Cost
Cross cutting	Severe weather	Increase resources for more frequent maintenance	Distribution infrastructure damage	Policy and Planning	
Cross cutting	Temperature increases	Track changes in annual high temperatures and resulting peak load to determine need for future capacity increases	Distribution capacity and efficiency reductions	Policy and Planning	
Cross cutting	Coastal storms	Increase the use of distributed generation and storage	Reduce customer outage magnitude and frequency	Policy and Planning	
Cross cutting	Coastal storms	Purchase or lease mobile transformers and substations	Reduce customer outage magnitude and frequency	Policy and Planning	

Bruzgul, J., R. Kay, B. Rodehorst, A. Petrow, T. Hendrickson, M. Bruguera, K. Collison, D. Moreno, D. Revell, 2018. Rising Sea and Electricity Infrastructure: Potential impacts and adaptation options for San Diego Gas and Electric, California's Fourth Climate Change Assessment.

Ebinger, J. and Vergara, W. (ESMAP and the World Bank), 2011.

Hammer, S. A., J. Keirstead, S. Dhakal, J. Mitchell, M. Colley, R. Connell, R. Gonzalez, M. Herve-Mignucci, L. Parshall, N. Schulz, M. Hyams, 2011: Climate change and urban energy systems. Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network, C. Rosenzweig, W. D. Solecki, S. A. Hammer, S. Mehrotra, Eds., Cambridge University Press, Cambridge, UK, 85–111.

Seattle City Light, 2013. Seattle City Light Climate Change Vulnerability Assessment and Adaptation Plan.

U.S. DOE, 2010. Hardening and resiliency: U.S. energy industry response to recent hurricane seasons.

U.S. DOE, 2016. Climate Change and Electricity Sector: Guide for climate change resilience planning.

U.S. DOE, 2016. Climate Change and the Electricity Sector: Guide for Assessing Vulnerabilities and Developing Resilience Solutions to Sea Level Rise.

WECC, Energy-Water-Climate Change Risk Analysis Presentation.

Annex 5. Climate Change Adaptation Funds

Multilateral and bilateral climate funds are key sources of adaptation finance. The key features of a subset of these different channels of public climate finance for beneficiary countries are summarized in Figure A5-1, including the areas of support (adaptation, mitigation or cross-cutting) and the instruments used to deliver climate finance. Sources of multilateral and bilateral adaptation funds are listed below.[84] The sources presented are not exhaustive.

Figure A5-1: Characteristics of international public climate finance flows in the period 2015–2016[85]

	Annual average USD billion	Area of support				Financial instrument		
		Adaptation	Mitigation	REDD-plus[a]	Cross-cutting	Grants	Concessional loans	Other
Multilateral climate funds[b]	1.9	25%	53%	5%	17%	51%	44%	5%
Bilateral climate finance[c]	31.7	29%	50%	–	21%	47%	52%	<1%
MDB climate finance[d]	24.4	21%	79%	–	–	9%	74%	17%

Multilateral Funds[86]

- Global Environment Facility (GEF) Trust Fund:
- Other GEF -hosted Trust Funds:
  - Special Climate Change Fund
  - Least Developed Countries Fund
  - Adaptation Fund: GEF acts as secretariat and WB as trustee
- Africa Climate Change Fund (African Development Bank (AFDB))
- Climate Investment Funds (implemented through WB, Asian Development Bank, AfDB, European Bank for Reconstruction and Development, and InterAmerican Development Bank)
  - Clean Technology Fund
  - Strategic Climate Fund
    - Scaling Up Renewable Energy Program
    - Pilot Program on Climate Resilience
- Green Climate Fund (WB is a trustee)
- Sustainable Development Goals Fund- Climate Action
- Global Energy Efficiency and Renewable Energy Fund (hosted by European Investment Bank)
- Global Facility for Disaster Reduction and Recovery (GFDRR) Trust Fund (managed by WB)

Bilateral Funds

- Global Climate Partnership Fund (Germany, UK and Denmark)
- International Climate Fund (UK)
- International Climate Initiative (Germany)

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[84] Watson, C., ODI and L. Schalatek, HBS. 2018. The Global Climate Finance Architecture. https://climatefundsupdate.org/publications/the-global-climate-finance-architecture-2018/

[85] UNFCCC (2018). Third Biennial Assessment and Overview of Climate Finance Flows. UNFCCC Standing Committee on Finance, Bonn, Germany. Available at: https://unfccc.int/topics/climate-finance/resources/biennial-assessment-of-climate-finance

[86] Watson and Schalatek 2018

Annex 6. Climate Risk Management Methods and Tools

This Annex provides a set of tools and resources for task team leaders that can be used to undertake climate risk management:

- Table A6-1 includes a list of climate risk screening tools for power sector projects,
- Table A6-2. includes a set of methodologies that can be applied to identify robust adaptation strategies, given climate change uncertainties

Table A6-1: Example Climate Risk Screening Tools for the Energy Sector[87]

Resource Name	Provider	Scale	Scope		Summary; Energy Component(s)	Publicly available?	Level of Effort
			Risk Screening	Adaptation			
Climate Safeguards System (CSS)	AFDB	Project-Level	✓	✓	Module 1 is a climate screen using scorecards to assign the project to one of three levels of vulnerability. Energy is one of the sectors included in CSS.	No	Low
Hydropower Screening Tool	USAID	Project-Level	✓	✓	Tool for hydropower developers and investors to evaluate potential climate change impacts on regulatory, reputational, and financial business objectives. Recommends steps for adaptation measures based on identified risks.	Yes	Low
Climate & Disaster Risk Screening Tools: Energy Sector	World Bank	Project-Level	✓		Tool for energy project developers to evaluate potential impacts of current and potential future climate change, with modules for: thermal power, hydropower, other renewables, energy efficiency, transmission and distribution, and energy capacity building.	Yes	Medium

[87] USAID. 2019. Climate Risk Screening Tools for Low-Emission Energy Development. Part of "RALI Series: Promoting Solutions for Low Emission Development." Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/2019_USAID_RALI%20Series%20-%20Climate%20Risk%20Screening.pdf

Resource Name	Provider	Scale	Scope		Summary; Energy Component(s)	Publicly available?	Level of Effort
			Risk Screening	Adaptation			
Climate Risk Screening and Management Tools for Strategy, Project, and Activity Designs	USAID	Strategy-, Project-, and Activity-Level	✓	✓	Includes an Annex for Infrastructure, Construction and Energy.	Yes	Medium
Aware for Projects ™	Acclimatize, used by ADB	Project-level	✓		Geography-based multi-hazard analysis; applicable across sectors (without particular detail or information per sector).	No	High
Hands-on Energy Adaptation Toolkit	World Bank	Power Sector-Level	✓	✓	A stakeholder-based, semi-quantitative risk-assessment to prioritize risks to a country's energy sector and identify adaptation options.	Yes	High
Broad screen, as described in the Sustainability Guideline	KfW Development Bank	Project-Level	✓	✓	Risk screen is part of a social, environmental, and climate due diligence appraisal. There are sector-specific sustainability criteria for energy (with a focus on renewables).	No	Unknown
Climate risk management system (under development)	European Investment Bank	Project-Level	✓		EIB recently developed and piloted a climate risk management system that includes consideration of climate risks, focusing on the energy and transport sectors.	No	Unknown
Climate risk scan and screen (under revision)	Inter-American Development Bank	Project-Level	✓		IDB is currently revising its climate-related disaster risk scan and screen and plans to mainstream screening investments in 2018.	Pending	Unknown

Table A6-2. Example Methodologies for Identifying Robust Adaptation Measures[88]

Approach	Definition	Pros and Cons
No-regret / low-regret	Low-regret adaptation decisions perform reasonably well compared to the alternatives over a wide range of future climate states and typically have positive net benefits over the entire range of anticipated future climate states	• Can be low cost, easy to implement • typically have positive net benefits over the entire range of anticipated future climate states • Limited strategies, typically represent increased efficiency, or operational measures, and exclude capital intensive investments
Precautionary principle/safety margins	Conservative approach to addressing uncertainty by apply the "precautionary principle" and/or incorporating safety margins	• Unlikely that design conservatism and safety margins can adequately address future uncertainties • Less common in practice due to budgetary constraints, and increased emphasis on operational and economic efficiency
Sensitivity Analysis	Sensitivity analysis is a method for assessing the effect of uncertainty on system performance, which considers the possible costs of making alternative choices to some "optimal" decision	• Does not address the question of what decision should be made when the future is unknown • Most useful when the optimum strategy is relatively insensitive to key assumptions •Can lead to strategies vulnerable to surprises
Cost-benefit analysis (CBA)	BCA under uncertainty generally requires estimates of possible future states as well as the probability of those states occurring. This information can then be used to calculate the expected net present value of future benefits and costs of competing projects. Subsequently, an optimal solution can be found that maximizes economic benefit or some other performance criterion	• Allows the planner to determine how strategies will perform under different plausible futures • Commonly used practice, which promotes a high level of engagement with stakeholders and is easily communicated • Requires agreement by planners, decision makers which can be challenging • Difficulty accounting for benefits of adaptation, particularly when indirect (i.e. societal) benefits are present, or when

[88] Modified from: "Garcia, L.E., J.H. Matthews, D.J. Rodriguez, M. Wijnen, K.N. DiFrancesco, and P. Ray. 2014. Beyond downscaling : a bottom-up approach to climate adaptation for water resources management (English). Washington, DC : World Bank Group. Available at: http://documents.worldbank.org/curated/en/204591468124480946/Beyond-downscaling-a-bottom-up-approach-to-climate-adaptation-for-water-resources-management" and "Water Utility Climate Alliance. 2010. Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning. United States. https://www.wucaonline.org/assets/pdf/pubs-whitepaper-012110.pdf"

Approach	Definition	Pros and Cons
		climate impacts or efficacy of adaptation measures are uncertain • There is limited experience to date with cost-benefit analysis of climate adaptation for the energy sector, particularly in a development context to date. Sources for U.S.-based analyses that planners may find useful are contained in the footnote[89]
Stochastic optimization/ Multi-objective robust optimization	Multiple future scenarios are weighted probabilistically. Multi-objective robust optimization extends stochastic optimization to explicitly make it more robust to challenging scenarios	• Stochastic optimization offers a straightforward, first-order approximation of hedging against unfeasibility
Adaptive management	A structured, iterative process that requires adaptive system components, including institutions, infrastructure, policy and regulations. A continuous process of adjustment, such as through a flexible adaptation pathways framework, that attempts to deal with the increasingly rapid changes in our climate, societies, economies, and technologies	• Requires adaptive institutions, and flexible operations

[89] San Francisco Department of Environment. "Solar and Energy Storage for Resiliency." December 2018. https://sfenvironment.org/sites/default/files/fliers/files/sfe_en_solar_resilient_cost_benefit_analysis.pdf; National Association of Regulatory Utility Commissioners (NARUC), "The Value of Resilience for Distributed Energy Resources: Overview of Current Analytical Practices," 2019, https://pubs.naruc.org/pub/531AD059-9CC0-BAF6-127B-99BCB5F02198.

Approach	Definition	Pros and Cons
Real options	Real options analysis is an established probabilistic decision process by which adaptability can be explicitly incorporated into project designs in an effort to avoid potential regrets associated with either over-investment or underinvestment in adaptation measures	• Identifies flexible and unique investment strategies, while providing flexibility within projects because they can be adjusted over time • Promotes management of risks instead of reacting to them • Helpful when comparing the benefits of one project over another is difficult • Can be complicated and time-consuming because of the inputs, analysis required, and high computing requirements • Decision makers must be heavily involved in this method • The process, results, and concept of flexibility are difficult to communicate
Robust decision-making	An iterative decision framework to identify strategies that perform reasonably well over a wide range of plausible future scenarios	• Provides information on the quality and performance of scenarios across large ensembles of plausible futures, which can be particularly advantageous to decision makers • Requires sophisticated computing and analytic capabilities • Can be more difficult to understand and explain than traditional scenario planning and requires a high level of decision-maker engagement
Breakeven analysis	Similar to benefit-cost analysis, but reframes calculations in terms of the minimum conditions required to "break even" on expenditures	• Allows for a simplification of uncertainty projections into the determination of a reasonable lower bound of risk, rather than a precise expected value

Approach	Definition	Pros and Cons
Scenario Planning	Scenario planning can be used to determine how current or proposed strategies should be adapted or incorporated into decision-making	• Allows the planner to determine how strategies will perform under different plausible futures • Transparent process, which promotes a high level of engagement with stakeholders and is easily communicated • There must be agreement by planners, decision makers, and stakeholders on scenarios or potential futures, which may prove difficult • Requires critical uncertainties to be identified and plausible scenario paths developed
Monte carlo analysis	A mathematical technique that allows accounting for risk in quantitative analysis and decision making. Monte Carlo simulation furnishes the decision-maker with a range of possible outcomes and the probabilities that will occur for any choice of action. It shows the extreme possibilities—the outcomes for the worst conditions and for the most conservative decision, along with consequences for intermediate decisions	• Allows for detailed outputs such as confidence intervals • Requires probability distributions of the climate stressor(s), which are difficult to estimate under changing climate conditions • Requires sophisticated computing and analytic capabilities • Model uncertainty ignored

A.6.3. Resources on Methodologies

Garcia, L.E.; Matthews, J.H.; Rodriguez, D.J.; Wijnen, M.; DiFrancesco, K.N.; Ray, P.. 2014. *Beyond downscaling : a bottom-up approach to climate adaptation for water resources management (English)*. Washington, DC : World Bank Group.
http://documents.worldbank.org/curated/en/204591468124480946/Beyond-downscaling-a-bottom-up-approach-to-climate-adaptation-for-water-resources-management
https://agwaguide.org/docs/Garcia_et_al_2014.pdf

Water Utility Climate Alliance. 2010. Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning. United States. https://www.wucaonline.org/assets/pdf/pubs-whitepaper-012110.pdf

Resilient Energy platform: https://www.nrel.gov/usaid-partnership/resilient-energy-platform.html

Willis, Henry and Kathleen Loa, "Measuring the Resilience of Energy Distribution Systems." RAND Corporation. 2015. https://www.rand.org/pubs/research_reports/RR883.html

Hallegatte, Stéphane. 2009. "Strategies to Adapt to an Uncertain Climate Change." Global Environmental Change 19(2): 240–47.

Hallegatte, S., A. Shah, C. Brown, R. Lempert, and S. Gill. 2012. "Investment Decision-Making Under Deep Uncertainty—Application to Climate Change." SSRN Scholarly Paper ID 2143067. Rochester, NY: Social Science Research Network. http://papers.ssrn.com/abstract=2143067.