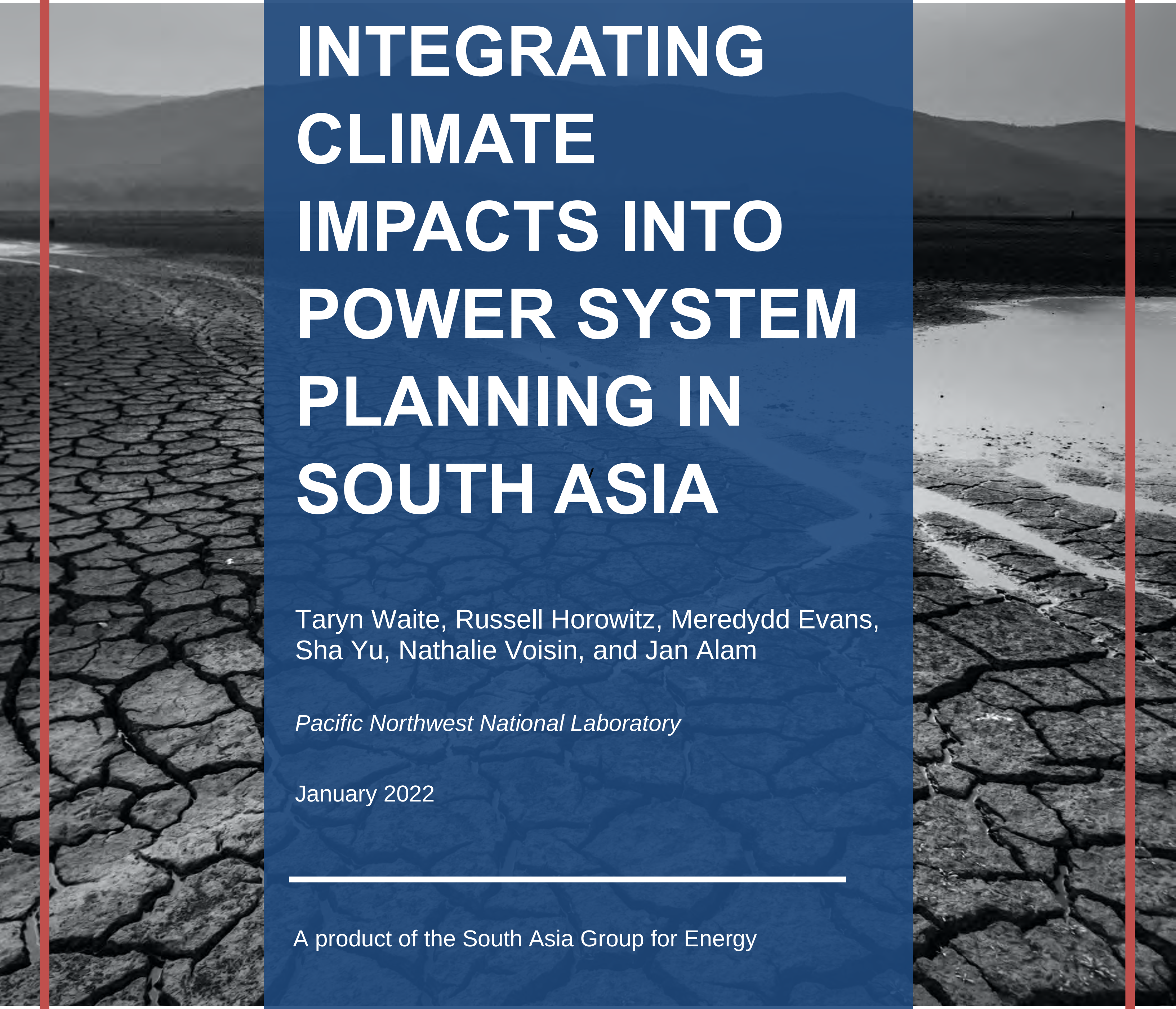

INTEGRATING CLIMATE IMPACTS INTO POWER SYSTEM PLANNING IN SOUTH ASIA

Taryn Waite, Russell Horowitz, Meredydd Evans, Sha Yu, Nathalie Voisin, and Jan Alam

Pacific Northwest National Laboratory

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A product of the South Asia Group for Energy

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Acronyms and Abbreviations

AC	air conditioning
CMIP	Coupled Model Intercomparison Project
ESM	Earth system model
GHG	greenhouse gas
GLOF	glacial lake outburst floods
SAGE	South Asia Group for Energy

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1.0 Introduction

South Asia's power sector will be able to meet the region's rapidly growing energy demand while accommodating increasing shares of renewable energy by engaging stakeholders in how to consider threats to power sector reliability and resilience from climate change. These threats include increased stress on and reduced efficiency of production and distribution systems, decreased reliability of resources needed for generation, and risk of infrastructure damage (Asian Development Bank, 2012). Protecting the power sector's reliability in the face of climate change will require grappling with uncertainty, coordination between diverse stakeholders, and institutional flexibility.

The South Asia Group for Energy (SAGE) is a group of energy and climate researchers working with stakeholders in the South Asian countries of Bangladesh, Bhutan, India, Maldives, Nepal, and Sri Lanka to facilitate reliable, resilient, and sustainable energy development in a changing world. SAGE includes researchers from Pacific Northwest National Laboratory, the National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory and operates with support from the South Asia Regional Energy Hub and USAID/India. An essential component of the group's work includes understanding how climate change will affect power demand, generation, and distribution as well as navigating the sphere of associated adaptation strategies.

SAGE conducted a series of discussions with stakeholders in four SAGE countries (Bangladesh, India, Nepal, and Sri Lanka) to identify key challenges and needs for power sector planning and decision-making. Stakeholders expressed concern about a range of climate change impacts, including impacts of flooding on infrastructure, changes to water availability, and impacts of heatwaves on peak demand. There was also emphasis on integrating specific regional vulnerabilities into planning and on strengthening backup and storage systems to maintain reliability. Planning needs included data and modeling tools to understand how power reliability and resilience will respond to both climate impacts and shifting generation mixes. Along with holding stakeholder discussions, we also conducted a survey of stakeholders in SAGE countries. Survey questions included asking stakeholders about specific climate impacts with which they were most concerned as well as their needs for maintaining reliability and resilience in the power sector.

To accompany this stakeholder engagement and set the stage for future collaboration, this report prepared by Pacific Northwest National Laboratory will highlight the major existing and expected climate change impacts on power system reliability and resilience in South Asia, with a focus on the ways in which climate impact information can inform decision makers in the power sector. After identifying climate impacts, we discuss pathways for developing modeling tools and experiments that inform planning to respond to these threats. The first section will give an overview of observed historical and projected future trends in climate change globally and in South Asia. The second section will describe the implications of South Asia's most pertinent climate change impacts on the power sector, including impacts on energy demand, generation resources, and infrastructure resilience. The final section will focus on planning strategies and on highlighting data, model, and policy needs.

2.0 Climate Change Overview

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021), emissions of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), have been on the rise due to human activities since about 1750, with continued growth in the past decade. It is estimated that human activities have caused an unprecedented rapid global air temperature increase of up to 1.3 °C since the late 1800s. Anthropogenic climate change has also likely altered global precipitation patterns, induced glacier retreat and sea level rise, and led to increasing frequency and intensity of extreme weather events (IPCC, 2021).

A widely used set of model scenarios project how future social, economic, and demographic changes and economic growth will shape GHG emissions and subsequent climate change impacts through the end of the 21st century.[1] The pathways range from a very-high-emission scenario with CO_2 emissions doubling by 2050, to a scenario with rapidly declining CO_2 emissions that reach net zero by 2050. Average global surface temperatures are expected to continue rising under all scenarios, with the magnitude of warming depending on the emissions level. Compared to the historical baseline, models predict a 1.0 °C to 1.8 °C increase under the very-low-emission scenario and a 3.3 °C to 5.7 °C increase under the very-high-emission scenario. This projected warming will increase the frequency and intensity of weather extremes, including heatwaves, heavy precipitation, and droughts, and will lead to continued snow and ice cover decline and sea level rise (IPCC, 2021).

2.1 Climate Change Impacts in South Asia

South Asia is a hotspot for climate change risks (Byers et al., 2018), with growing implications for critical infrastructure including power systems. The region is expected to experience more warming in the coming decades than the global average, with a projected average increase of around 2.1 °C by the end of the century compared to the 1995–2014 baseline period in a moderate emissions scenario and around 4.3 °C in the highest emissions scenario (Figure 1). While warming will occur throughout the entire region, the most intense warming is expected in the northwestern mountainous regions encompassing the Karakorum and Himalayan mountain ranges (Almazroui et al., 2020). These regions will experience a decline in snow cover and snow water equivalent (IPCC, 2021), as well as continued glacier retreat. South Asia is expected to lose approximately 50% of its glacier ice volume by the end of the 21st century due to warming (Huss et al., 2017). Heat waves are also expected to increase throughout South Asia in both frequency and severity. For example, under a moderate emissions scenario associated with a global temperature increase of about 2 °C, India's heat waves will increase in frequency by about one event per 20 years and in length by 4–7 days per decade (Rohini et al., 2019). If future emissions reach the levels represented by the highest emissions scenario, these impacts on heat waves will be much more severe (Vinke et al., 2017).

Climate change will also affect the magnitude, seasonality, and timing of precipitation throughout South Asia. Summer monsoon precipitation is expected to increase on average through the end of the century (Huo and Peltier, 2020), driving increases in average annual precipitation (Figure 1). However, the region will also see rising interannual monsoon variability, meaning that there will be more years in which rainfall is either unusually high or low (Menon et al., 2013). Monsoon variability will increase on a seasonal scale as well, with higher frequencies of both extreme precipitation events and short-term dry

[1] The scenarios referred to here are those combining shared socioeconomic pathways (SSPs) and representative concentration pathways. They range from a very-high-emissions scenario (SSP5-8.5) to a very-low-emissions scenario (SSP1-1.9).

spells (Vinke et al., 2017). Climate change will also alter the timing of the monsoon, leading to an annual delay in its onset (Ashfaq et al., 2021). Changes to winter precipitation are more uncertain and spatially variable than summer monsoon projections, but models suggest that there will be a trend toward drier winters in some areas (Almazroui et al., 2020).

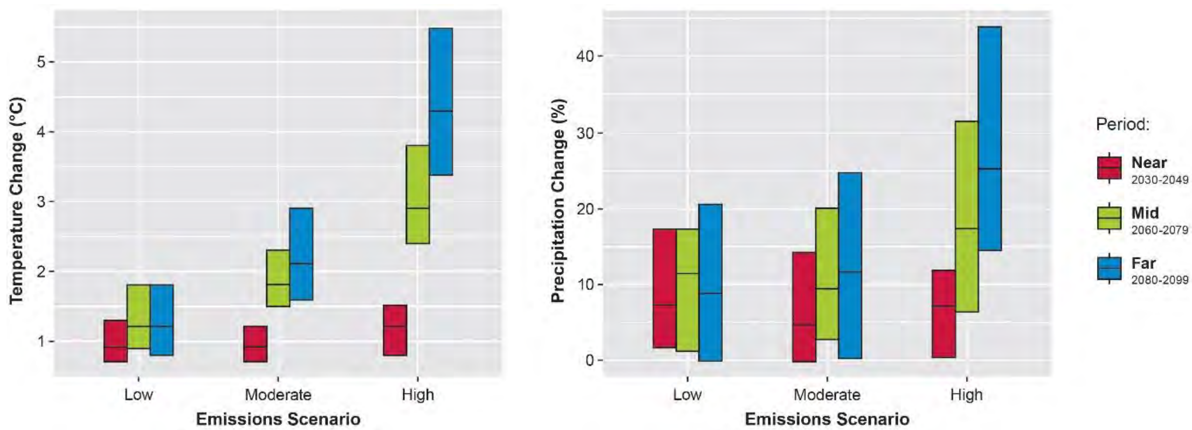

Figure 1. Projected change in average annual temperature (left) and annual precipitation (right) from the historical baseline period (1995–2014) in the near (2030–2049), mid (2060–2079), and far (2080–2099) future periods in South Asia under scenarios with low, moderate, and high future GHG emissions. Each bar represents the multi-model 66% likely range, while black lines in each bar represent the median projection. Source: Almazroui et al., 2020

South Asian countries with significant coastal regions, including India, Bangladesh, Sri Lanka, and the Maldives, will face the compounded challenges of tropical cyclone intensification and sea level rise under climate change. As sea surface temperatures rise, tropical cyclones will become more severe, leading to increases in heavy rainfall and extreme wind speeds during these destructive storms (IPCC, 2021). Global mean sea level rise is projected to reach about 0.56 meters by 2100 in the moderate emissions scenario (IPCC, 2021). Sea level rise and associated coastal retreat will act as a risk amplifier for South Asia's coastal regions, increasing the severity of tropical cyclone storm surges and the risk of extreme flooding during these storms (Woodruff et al., 2013).

3.0 Exposure of the Power Sector to Climate Change

Climate change has and will continue to affect South Asia's power sector through changes to energy demand, resource availability, and infrastructure resilience. Figure 2 depicts some of these potential impacts. Under future climate change scenarios, warming and heat waves will drive up demand and increase stress on power systems while also decreasing their efficiency due to rising air and water temperatures. With changes to precipitation patterns as well as snow and ice conditions, water resources will become more variable and inconsistent, threatening the reliability of hydropower and thermal power plants. Lastly, infrastructure damage will become an increasingly prevalent risk as the frequency and intensity of extreme weather events increases, heightening threats from flooding, storms, and sea level rise.

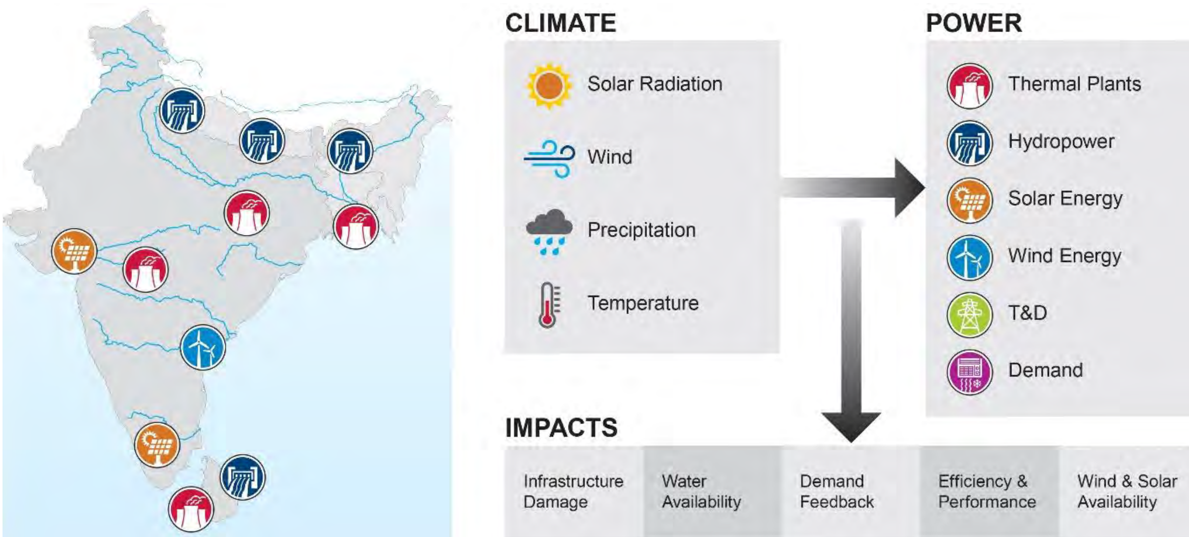

Figure 2. Example impacts of climate change on the power sector in South Asia.

3.1.1 Electricity Demand

Both rising average air temperatures and increasing heat wave frequency and severity will drive up energy demand for cooling, increasing stress on electricity grids. Air conditioning (AC) ownership in South Asia is still relatively low, with only 4% of Indian households owning an AC in 2016 (IEA, 2018). However, ownership is expected to grow significantly due to rising incomes in the coming decades. The combined impacts of growing AC ownership and climate change will drive up the energy demand for cooling; for example, India may see a 15-fold increase in cooling demand by 2050 (IEA, 2018).

Heat waves will be particularly impactful because they pose challenges for meeting peak demands. Power systems in South Asia have already been struggling with heat waves over recent decades. During episodes of extreme heat, sudden increases in energy demand for cooling can overload the grid, causing power outages. In 2011, extreme summer heat in Bangladesh left residents without power for 9–10 hours and 15–18 hours per day in urban and rural areas, respectively (Shahid, 2012). An island-wide blackout during a heat wave in March 2016 left Sri Lanka without power for 6 hours, resulting in disruptions to water supply (Times of Sri Lanka, 2016). A heat wave in the city of Agra, India, caused widespread power outages in summer 2021 as energy demand climbed to a record high (Qureshi, 2021). More frequent and severe heat waves compounded with economic growth will trigger an increase in AC ownership, driving increasing peak demand during heat waves. In Hong Kong, where AC ownership is already very high, energy demand for cooling increases by 80% to 140% during extreme heat events

(Morakinyo et al. 2019). The predicted trend in heat wave frequency and severity due to climate change puts peak demand load at the forefront of ongoing challenges for South Asia's power sector.

3.1.2 Generation Resources (Inputs)

Changes to the availability and reliability of water resources will pose major challenges for the power sector in South Asia due to the high demand for water of both hydropower and power plant cooling. **Projected increases in annual precipitation variability and changes to monsoon timing may threaten the reliability of water resources needed for power generation**. During low-rainfall years and when the monsoon is significantly delayed, prolonged drought conditions could lead to widespread shortages of the water required for both power plant cooling and hydropower generation. In 2012, a delayed monsoon both directly decreased hydropower production and indirectly strained the energy sector's water supply through increased demand for irrigation. These stressors likely contributed to the massive power outage that occurred in July and affected almost half of India's population.

Along with these changes in annual precipitation regimes, **rising seasonal variations in precipitation and increasing prevalence of dry periods will also threaten the reliability of water resources needed for thermal plant cooling and hydropower**. These changes to precipitation regimes are reflected in projected streamflow patterns for the region. While average yearly streamflow will likely increase due to monsoon intensification, dry spells will become more prevalent and intense throughout the dry season (Zhou et al., 2018). This threatens the reliability of power generation because thermal power plants require consistent water input throughout the whole year unless enough storage and regulation can be provided by man-made reservoirs.

Water resources for power generation in high mountain regions will also be affected by rising temperatures causing glacier recession, lower snowpack, and earlier snowmelt. While in the short term, increased glacial melt may increase streamflow, this represents a permanent loss of water resources that threatens the long-term viability of projects that depend on this flow (Schaner et al. 2012). Much of flow in the Koshi river basin, which contributes about 27% of Nepal's total hydropower potential, comes from snow and glacier melt. The sub-basins of the Koshi with the highest melt contributions receive up to 20% of their flow from snow and glacier melt in the wet season and 59% in the dry season (Chhetri et al., 2021). Rising interannual variation in streamflow due to loss of glacier water storage will decrease the reliability of hydropower in the far future. Impacts of glacier retreat on the power sector are particularly concerning given that streamflow reductions in glacier catchments will occur in the summer, coinciding with peak energy demand for cooling (Laghari, 2013). Thus, while annual streamflow in these catchments may remain constant or even increase in the short term due to glacier melting, changes to the timing of peak streamflow will have implications for power system stability. Impacts of warming on water resources will also extend to areas downstream of the high mountain regions because glacier melt contributes to much of the dry season flow of major rivers that supply water to these areas (Barnett et al., 2005).

While glacial retreat will compromise hydropower reliability in the far future, reductions in snow cover due to rising temperatures will affect sub-annual streamflow timing in the near and long term. Two of India's largest hydropower projects, Nathpa Jhakri and Bhakra Nangal, will suffer decreased generation in spring and early summer due to declining snowmelt (Ali et al., 2018). There may not be an overall loss of streamflow input from snowmelt for hydropower generation annually, but stakeholders will need to consider changes to the seasonality of hydropower potential to assure that energy demand is met consistently throughout the year.

Rising ambient temperatures due to climate change will also increase the temperature of water resources, reducing the efficiency and output of thermal power plants that utilize cooling water.

The thermal efficiency of a power plant system depends on the temperature difference between the cooling water and steam. Thus, as cooling water temperature increases, performance is limited. For example, nuclear power plants see reductions in thermal efficiency and power output by up to 0.44% and 0.15%, respectively, per degree Celsius of warming (Attia, 2015; Durmayaz and Sogut, 2006). Additionally, thermal pollution regulations are often in place to limit the negative environmental impact of heated water discharged by power plants. The combination of reduced thermal efficiency and regulatory limitations can lead to economic impacts on the power sector; a German model, for example, found that rising river temperatures are associated with increasing electricity prices (McDermott and Nilsen, 2014).

While water availability will be the primary concern for energy generation resource vulnerability in South Asia, climate change will also affect wind and solar resources. Projections of wind speed and air density under future climate scenarios are uncertain and highly spatially variable. For example, an assessment of three proposed offshore wind energy sites in India found that wind speed persistence is expected to decrease at two of the sites and increase at the third under a moderate climate change scenario (Kulkarni et al., 2015). The magnitude of climate change impacts on solar power generation potential is also relatively uncertain and varies between emissions scenarios. As warming continues, heightened evaporation will increase atmospheric water vapor content, which will slightly reduce solar radiation. Models predict that solar radiation will decrease in India by 0.5% to 4% through the middle of the century, with northern India affected the most. This decline will persist through the end of the century under high-emission scenarios, while solar radiation will recover under low- to moderate-emission scenarios. While the solar radiation declines predicted on average by multiple models are likely not extreme enough to significantly affect solar photovoltaic potential, there is substantial variation between different models' results, and some individual models predict more severe impacts (Ruosteenoja et al., 2019). Additionally, warming could directly affect solar photovoltaic potential due to lower efficiency when ambient temperatures are higher (Radziemska, 2003).

3.1.3 Infrastructure

Of the global population affected by flooding, 64% lives in South Asia (World Bank, 2012), and climate change will exacerbate existing flood and landslide risks. Flooding and landslides pose significant threats to human health and the economy, including energy infrastructure. For example, in August 2014, damage from a landslide after a heavy rainfall event disconnected almost 10% of Nepal's hydropower supply (Bhatt, 2017). After heavy monsoon rainfall in 2015, severe floods in the city of Chennai, India, inflicted over 30 million USD in damage to the power sector and caused a deadly outage at a hospital (The Guardian, 2015; Dominique, 2015). **As climate change intensifies monsoon rainfall and increases the magnitude and frequency of extreme precipitation events, damaging floods and landslides will become more common and severe**.

In the high mountainous regions of South Asia, climate change will worsen flood risks in the near future due to the impacts of warming on glaciers. Rising rates of ice melt from glacier recession will lead to the expansion of existing glacier lakes and the formation of new ones. While these impacts may increase the potential for hydropower expansion in the Himalayas in the short term (Farinotti et al., 2019), they will also increase the risk of glacial lake outburst floods (GLOFs). These floods, which can be virtually impossible to predict and are often devastating, occur when the dams containing glacial lakes fail due to increased water pressure and other natural hazards. In 2016, a GLOF caused by heavy rainfall resulted in significant damage to Nepal's Upper Bhote Koshi hydropower plant (Figure 3) as portions of the plant were submerged and debris carried by the flood destroyed structural components (Bruen et al., 2017). GLOF risk in the region could rise threefold as glaciers recede (Zheng et al., 2021), leaving conventional hydropower plants in South Asia's high mountains increasingly vulnerable.

Figure 3. Damage to Nepal's Upper Bhote Koshi hydropower plant after a 2016 glacial lake outburst flood caused by a heavy rainfall event.

Rising frequency and severity of extreme precipitation events will also threaten energy infrastructure through the impacts of erosion. Combined with ongoing disturbance from land use change, heavier monsoon rainfall will worsen soil erosion throughout South Asia (Pal et al., 2021). This will contribute to higher sediment loads in streams, which can damage and wear down hydropower infrastructure, limiting its longevity (Koirala et al., 2016). High sediment loads may also lead to increased reservoir siltation, which occurs when silt builds up in a reservoir and reduces the amount of water that can be stored for electricity generation. Climate change impacts on reservoir siltation are particularly concerning in areas where land use practices already pose erosion challenges. In Sri Lanka, high rates of soil erosion due to agriculture is a threat to hydropower generation; without changes to land use practices, soil erosion and subsequent reservoir siltation will be costly to hydropower plants in Sri Lanka (Udayakumara and Gunawardena, 2016). This threat will be amplified as extreme precipitation leads to a rise in erosion rates under climate change.

The intensification of tropical cyclones due to climate change will be a significant risk to the energy sector in South Asian countries with coastal regions, including India, Sri Lanka, and Bangladesh. Strong winds and flooding during these storms can damage production, transmission, and distribution infrastructure. For example, in 2007, Tropical Cyclone Sidr caused failures at all major power plants in Bangladesh, severe damage to wind power infrastructure, and destruction of electricity and transmission lines (Shahid, 2012). The coastal state of Odisha, India, has also seen severe impacts in the past decade, with tropical cyclones Phailin (2013) and Fani (2019) inflicting a combined 1.4 billion USD in damage to electricity systems across the state (Mohanty et al., 2020). As climate change intensifies both the wind speeds and the amount of rainfall during tropical cyclones, the power sector will become increasingly vulnerable. One study found that a 20% increase in the mean value of wind speeds during extreme wind events could reduce reliability of transmission lines by more than 30% (Rezaei et al., 2016).

Stakeholders in coastal regions will also need to consider sea level rise and coastal retreat as a risk amplifier and major threat to energy sector infrastructure. The shorelines at 13 major ports along the Indian coast are projected to retreat by between 14 and 30 meters by the end of the century (Patil and Deo, 2020). One assessment found that in Tiruvallur, a coastal city in Tamil Nadu, India, a 1-meter rise in sea level could affect power plant infrastructure with a replacement value of over 3 million USD (Byravan et al., 2011). An estimated 30% of the power generation capacity in Bangladesh may need to be relocated due to risk of inundation from sea level rise by the end of the century (Khan et al., 2013). Sea level rise and the geomorphic changes associated with coastal retreat will amplify the impact of tropical cyclones, increasing rates of severe flooding from these storms (Woodruff et al., 2013). Thus, as sea levels continue to rise, power systems in coastal areas will become more prone to threats from tropical cyclones and flooding as described above.

4.0 Planning for Climate Change Impacts

We have presented a broad overview of potential climate impacts on the power sector in South Asia. Given the heterogeneity and uncertainty involved, long-term planning for the power sector must consider climate change to achieve the desired reliability and resilience. To plan for climate change, individual nations and stakeholders must identify their unique vulnerabilities and adaptation options and integrate this knowledge into their planning processes. Accounting for climate change in decision-making will additionally require building capacity in local institutions and changes in policies or institutional structures to assimilate climate information with diffuse consequences.

4.1 Assessing Vulnerability

Sensitivity to climate change will vary based on geography, demographics, and built infrastructure. To assess vulnerability, stakeholders therefore need data and tools relevant to their specific situation. Using such tools can help decision makers understand the range of possible impacts climate change may have on their operations. It is critical to note that because of the interconnectedness of power systems, their vulnerability is not simply a result of combining the vulnerability of individual components. Rather, vulnerability assessments must be able to represent the joint susceptibility of their parts as one system. Conducting such assessments may require changes in planning processes, priorities, and incentives. Existing planning processes may need to change so that these assessments inform decisions.

4.1.1 Data Needs

Assessing vulnerability to climate change begins with acquiring relevant climate projections (Gardiner et al., 2019; Mukhi et al., 2017). Data from modeling exercises such as the Coupled Model Intercomparison Project (CMIP) is widely available. These modeling experiments involve many Earth system models (ESMs) run under similar conditions and typically under a standard set of emission scenarios. This presents a challenge to planners because trends in temperature, precipitation, and extreme events are dependent on projected future GHG emissions. Even within an emissions scenario, the results from different models will vary, providing uncertainty information to climate projections that can better inform decision-making but that will also be challenging to interpret and integrate.

Another obstacle to using climate projections is that they are not provided in an easy format for decision makers to use and are often at too coarse a spatial or time scale to be relevant to those dealing with the effects of climate change on the ground (Chattopadhyay et al., 2016; Navarro-Racines et al., 2020). Spatially and temporally relevant climate projections may be obtained through a regional climate model or by downscaling ESM output (converting coarse results to granular results) with statistical or dynamical methods. For example, to obtain high-resolution projections of water availability, land surface scheme and hydrology models can be deployed using inputs from ESMs. Best practice is to use multiple sectoral models to quantify overall uncertainty for robust decision-making.

Planners will need to combine climate projections with information about their present and future operations. The specifics of this information may vary widely depending on the scope of the stakeholder and the question they hope to answer. For some stakeholders, the information needed may include grid configuration, generation expansion projections, specific generation siting plans, site-specific information such as topology, and/or load demand projections. **Our ability to represent the future for the power sector depends not only on internal factors, but also on external trends such as future population and GDP growth, electrification, and decarbonization policies**. Having a better grasp of all the factors and interconnections that affect their operations will improve the likelihood of properly accounting for the impacts of climate change.

4.1.2 Modeling Climate and Power System Dynamics

Ultimately, this climate and operational data must be integrated to understand the effects of climate change on the power system. This requires specialized tools and models that have been developed to represent the climate and power systems or their interlinkages. Detailed grid models provide a deep understanding of electricity sector operations, while multisector dynamic models provide a higher-level overview of how the electricity sector interacts with other aspects of the economy and climate. Techniques such as integrating multiple models, scenario analysis, and robust decision-making can maximize the utility of these models.

Power-system-specific models can help understand the effects of extreme events, changing resource availability and new generation types. These models are often deployed to test the ability of the system to withstand stressors. Using a power system model to conduct criticality analysis can provide insights into the most important measures to protect the power system. Criticality analysis aims to understand how the system would respond to single or multiple component failures. It can demonstrate vulnerabilities in the system and point to the most important components to protect. However, it's important that these types of analyses consider many types of external events, including high-impact, lower-probability events, such as devastating floods or compounded extreme weather events (Nicolas et al., 2019). This is especially important as high-impact events begin to occur more frequently due to climate change. These sector-specific models can provide specific insights into detailed electricity system processes but are often unable to capture interactions across sectors or regions.

To capture interactions, multisector dynamic models that consider connections between sectors can be utilized. **Multisector dynamic models, such as the Global Change Analysis Model, can help understand these interactions and how climate changes can affect multiple systems simultaneously**. For example, heat waves will affect power generation and infrastructure performance, as well as drive up electricity demand for space cooling. To understand how this pressure on supply and demand will play out, we need to know what the grid will look like in the future, how AC ownership rates will respond to both economic and climate factors, and how much demand increases during heat waves. A model that includes the electricity, building, and climate systems may provide more useful understanding than a power sector model with exogenous assumptions about future load and climate.

Alternatively, these kinds of complex problems can be studied by linking together multiple sectoral models. For example, in a study on the effect of climate change on water availability for the Western U.S. power grid, Voisin et al. (2020) use downscaled ESM output to drive a hydrology model. This hydrology model provides inputs to a river routing model, which is used to understand the impact on hydrogeneration and thermal power plant cooling. Grid-wide effects are then understood with the help of an integrated energy model. Linking multiple models allows scientists and decision makers to understand complex new phenomena without having to build new models from scratch. However, these studies can be challenging because of the requisite expertise in multiple models or the need to obtain data from other modeling studies.

Regardless of the modeling tool used, scenario analysis and robust decision-making are two strategies for providing an understanding of the uncertainty in outcomes and the range of possibilities. Scenario analysis involves constructing a range of possible assumptions about the future climate, available technologies, policies, and other inputs to models. Running a model under these different assumptions allows for a greater understanding of the possibilities for the future. This type of analysis can be performed with many types of models, including multisector dynamic models or stochastic planning models that utilize a probability distribution of the input likelihood. Robust decision-making is a similar approach but begins with the likely strategies a decision maker might implement and then attempts to test these strategies against the range of plausible futures (Mukhi et al., 2017).

While SAGE has experience with tools to assess climate vulnerability, these tools may need to be modified for the specific context of South Asian stakeholders. Repurposing existing models, building new ones, or combining models in new ways can all lead to better understanding of climate vulnerability. It is especially important that tools used for these assessments are easy for decision makers and scientists to implement and update. As climate change projections and power system plans change, vulnerability assessments need to be reassessed and revised to be most relevant to the system.

4.2 Integrating Modeling into Planning

It is crucial that power sector stakeholders collaborate with modelers on studies to enhance operation, management, and/or planning of the electricity system in response to climate change impacts. Figure 4 identifies some ways for stakeholders to engage in the modeling process. By actively participating in scenario design, decision makers can assure that the results of modeling exercises will be able to inform their decisions. In addition, planning must develop processes to incorporate knowledge gained from modeling studies, and local capacity building should occur to assure that studies and planning procedures can be updated. This is especially true for studying climate impacts because power sector stakeholders may not have established ways of using this information in their planning.

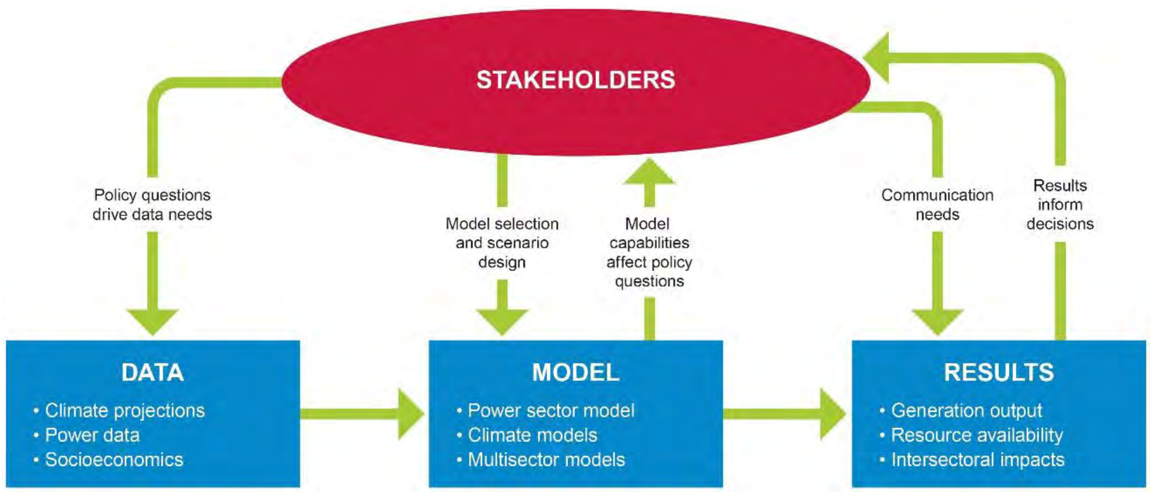

Figure 4. Diagram of stakeholder interactions with the modeling process. Some specific examples of data, model, and results for the climate–power nexus are listed.

4.2.1 Collaboration in Modeling

From the earliest conception of a modeling experiment, fusing the expertise of scientists and modelers with the institutional, political, and cultural understanding of power sector decision makers can help maximize the utility of model results. Stakeholders should help define the scope of the study based on their needs and potential uses. Scientists must communicate model capabilities so that stakeholders have proper expectations and knowledge of the model's potential value in the decision-making process. The spatial and temporal granularity of the model, assumptions in the model, and the resulting output are all important factors. For example, there is often a trade-off between using more granular power sector models versus coarser multisectoral dynamic models. The choice of which tool or set of tools to use should be made jointly between modelers and decision makers based on needs and capabilities.

In addition to their knowledge of specific needs and institutions, stakeholders may be able to contribute detailed and updated data or have connections to organizations with useful data and models. Incorporating this local knowledge may improve the model results and the political feasibility of the model as a decision-making tool. Additionally, stakeholders can help define certain assumptions and model inputs due to their richer knowledge of specific details about the power sector structure or interactions. This can improve model accuracy, but must be balanced with maintaining model objectivity to avoid predetermining the results (Süsser et al., 2021).

4.2.2 Use in Decision-Making

Models are particularly helpful for informing decisions that would benefit from knowledge about an uncertain future, such as the impacts from climate change. While no model can perfectly predict the future, they can capture complex dynamics that might otherwise be missed. **Modeling studies can help provide bounds on policy targets, demonstrate the impact of specific policies or external developments on the power sector, highlight trade-offs inherent in decisions, and/or evaluate the impact of already implemented policies**.

For models to provide evidence-based support to decision makers, the timely provision of well-contextualized modeling results is key. The planning process for decision makers should explicitly include support to develop modeling experiment scope and time for all stakeholders to discuss model results and their implications. Because stakeholders may not possess sufficient experience with climate, power, or multisectoral models to be able to contextualize their outcomes, they should involve modelers to communicate the results in relation to the model's assumptions and limitations.

4.2.3 Building Power Sector Capacity to Prepare for Climate Change

Power sector institutions will need to build internal capacity to prepare for climate impacts and implement solutions. Initially, this means increasing knowledge of the types of impacts that stakeholders must be aware of and the possible solutions to deal with these impacts (Mukhi et al., 2017). Internal capacity to process data and conduct some modeling exercises may be especially beneficial, particularly as plans need to be revisited.

Updating plans is extremely important because external factors and institutional goals change over time. New targets for decarbonization, advances in climate science, and changes in expected emissions trajectories will all change projections of climate impacts on the power sector. Implementing a process of data analysis, stakeholder input, and decision-making at regular intervals increases the chance that the power sector will be best prepared to deal with extreme events and environmental changes. For example, adaptive management is one approach to decision-making under uncertainty that involves regular prediction, implementation, monitoring, and updating based on outcomes (Williams et al., 2009).

Regularly updating plans and institutionalizing the use of models in the planning process is easier when the capacity to collect data, design studies, run models, and/or interpret results is developed internally. Many climate and power models are complex and computationally intensive, so it may not be feasible for stakeholders themselves to become users of these tools. Still, by actively participating in the modeling process, it can be easier for decision makers to develop and incorporate new experiments into future plans.

Coordination between stakeholders, across both regions and sectors, will also become increasingly important to power system reliability as climate change progresses. Many natural disasters, such as floods, droughts, and tropical cyclones, have transboundary impacts; the strongest efforts to protect power systems from these effects may therefore require regional stakeholder collaboration (UN, 2016). In addition, the extent to which climate change impacts will threaten South Asia's power sector depends on actions taken within other sectors. For example, as increased flooding due to climate change leads to worsening impacts of erosion and reservoir siltation on power generation, deforestation may amplify these impacts. Additionally, competition for water resources with other sectors, especially the agriculture sector, could affect changes to water availability for the energy sector under future climate change scenarios.

5.0 Conclusion and Next Steps

This report outlined the key climate interactions that the power system in South Asia will need to navigate. More frequent and powerful floods threaten electricity system infrastructure. Increases in heat waves and droughts will create challenges in meeting power demand. Meanwhile, the seasonal and annual availability of water, wind, and solar resources is likely to change, altering historical patterns of power generation.

The impacts that will most greatly affect specific regions within South Asia will depend on local geographic and socioeconomic factors. High mountain areas are particularly dependent on hydropower generation, making them vulnerable to glacial retreat and changes in precipitation and snowmelt. Coastal regions face rising sea levels that can combine with storms to produce devastating floods that threaten the resilience of the power grid. Many urban settings will struggle to deal with heat waves as residents increasingly use air conditioners to combat dangerously high temperatures. These concerns were widely echoed by stakeholders during our discussions with them.

Many stakeholders also completed surveys on power system resilience and reliability. The results demonstrate a broad range of needs to prepare for climate change, consistent with feedback received during stakeholder discussion meetings. There is interest in how a variety of factors may affect the power sector, with heat waves, flooding, and compound extreme events considered particularly threatening for most stakeholders (Figure 5a). To build resilience and reliability to these events, responses to the surveys reflected a desire for information and integration of climate change impacts in power sector planning (Figure 5b).

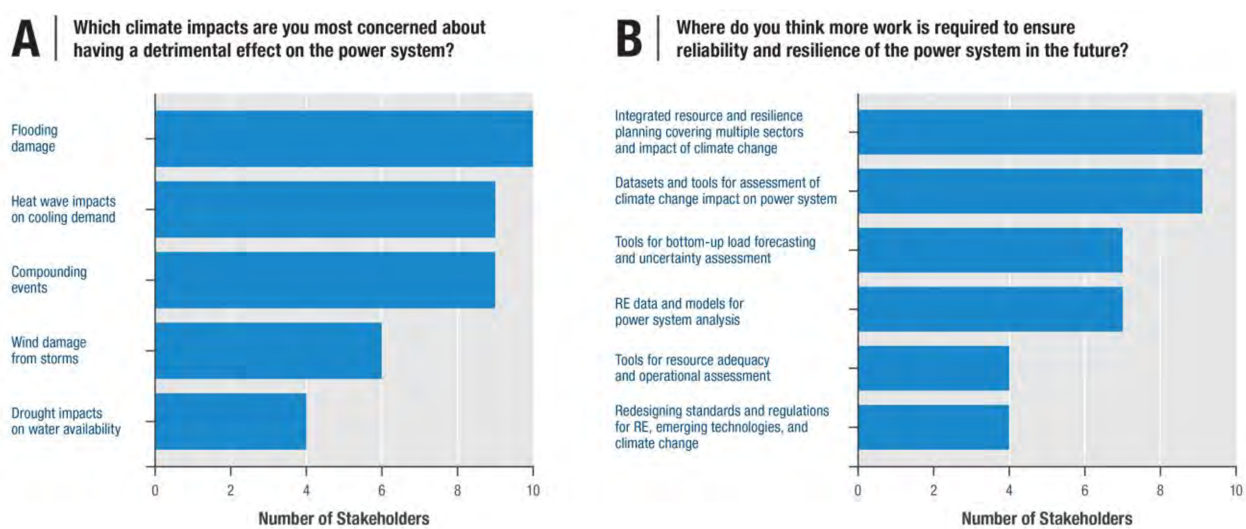

Figure 5. Stakeholder survey responses on (a) climate impacts of concern and (b) reliability and resilience needs. Responses were received from 13 stakeholders, from India (6), Bangladesh (4), Sri Lanka (2), and Nepal (1). Only answers with more than one response are included.

This need for greater information and resources to plan for climate change highlights the important role SAGE can have in facilitating informed decision-making for power sector planners. The national laboratories comprising SAGE have expertise with a variety of climate, power, and multisector modeling tools. By collaborating with stakeholders in South Asia, new modeling experiments can be designed to benefit decision makers. Following coordination on specific stakeholder needs, the implementation of these tools can demonstrate the impacts of changes to the climate and solutions to minimize negative effects on the power sector.

However, given the breadth of climate change and its potential impacts on the power sector, it is infeasible to address impacts for all stakeholders and countries with one tool or modeling study. One approach to deal with this limitation is to first focus on only a subset of climate impacts in selected regions. The specific impact can be informed by stakeholder concerns and be chosen to leverage pre-existing SAGE tools. The results from such a study would serve as a demonstration of capabilities that can then be used to develop follow-up studies to understand the effects of other climate impacts and in different regions. For example, SAGE has tools to model water resources that can be applied to better understand stakeholder concerns about flooding and water availability under different climate scenarios. An initial experiment could study the effects of changing water resources over a limited geographic or power sector scope, which could then be broadened in future studies.

No matter the study design, it will be important that future work builds off of the stakeholder feedback that was received in previous meetings and surveys. Stakeholders relevant to future work will be consulted in the study design, implementation, and results communication. By leveraging the local system knowledge of those working in the power sector in South Asia, in addition to the scientific expertise and quantitative rigor SAGE possesses, the grid can be made more resilient and reliable in the face of the threats that climate change presents.

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