RELIABILITY AND RESILIENCY IN SOUTH ASIA'S POWER SECTOR

Pathways for Research, Modeling, and Implementation

Mohit Joshi, David Palchak, Thushara De Silva, and Gord Stephen
National Renewable Energy Laboratory

February 2022

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Abstract

Reliability and resilience are the core principles of power system planning and operations around the world. Power systems in South Asia are transforming with the increasing penetration of clean energy generation resources, emerging technologies, and increasing electricity demand and electrification. At the same time, these power systems are facing challenges posed by extreme weather events and climate change. These factors add further importance to the reliability and resilience of future power systems in South Asia. This has motivated us to better understand the country-specific challenges and chalk out the pathways for research, modeling, and implementation in South Asia. Our research, experience in the region, and feedback from key stakeholders indicate that the following items are key areas in which more work is needed to improve the reliability and resilience of power systems in the region:

- Renewable energy data for power system studies
- New tools and studies
- Resilience planning
- Resource adequacy
- Advanced renewable energy forecasting
- Cybersecurity
- Load forecasting
- Coordinated planning and operations.

List of Acronyms

CAGR	Compound annual growth rate
CEA	Central Electricity Authority
DOE	U.S. Department of Energy
ENS	Energy not served
IRRP	Integrated resource and resilience plan
LOLP	Loss of load probability
NREL	National Renewable Energy Laboratory
SAGE	South Asian Group for Energy
USAID	U.S. Agency for International Development

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1. Introduction

Power systems around the world are changing because of the low cost of clean energy resources and a focus on decarbonization. These factors have led to a push toward the adoption of renewable energy (RE) resources and emerging technologies such as energy storage, distributed energy resources, electric vehicles, demand response, and other similar technologies. South Asian countries[1] have made several commitments to formalize the transition (Table 1). The transition to clean energy resources will have widespread impacts on the way the grid must be planned and operated, as the primary generation resources, likely wind, solar, and hydro, are more dependent on weather than fossil fuel-based generation. At the same time, power systems also must meet the increased expectations from consumers for reliability and manage the impact of extreme events such as cyclones, floods, droughts, and extreme high and low temperatures, which are more likely because of climate change (Mohanty 2020). Similar trends are also being witnessed by South Asian countries (Mohan 2021; Eckstein, Kunzel, and Schafer 2021). I

Table 1. Clean Energy Plans for Various South Asian Countries

Country	Specific Clean Energy Targets or Plans
India	• 500 GW capacity of clean energy resources by 2030 • 50% generation from renewable energy by 2030 • Net zero by 2070 (PIB 2021b)
Bangladesh	• National Solar Energy Action Plan • Business-as-usual scenario: 8 GW (10%) solar capacity by 2041 • Medium solar scenario: 25 GW (31%) solar capacity by 2041 • High solar scenario: 40 GW (50%) solar capacity by 2041 (Chowdhury 2020)
Bhutan	5 GW hydro generation capacity by 2030 (MOEAB 2021)
The Maldives	15% renewable energy in energy mix by 2030 (MOEM 2020)
Nepal	15,000 MW clean energy capacity by 2030 (conditional) (GON 2020)
Sri Lanka	70% generation from renewable energy by 2030 (MOES 2021)

Energy storage is also expected to have significant penetration in India in many different forms, such as utility-scale battery energy storage, pumped hydro energy storage, and electric vehicles. A similar role for energy storage is expected in other South Asian countries (Chernyakhovskiy et al. 2021). This would mean that the future South Asian power system would have large shares of renewable energy, hydro, and energy storage. South Asian countries are also at the forefront of climate change risks. Over the past several years, extreme events such as cyclones, earthquakes, floods, droughts, and high temperatures have directly impacted their power systems (Soonee et al. 2018). These events are expected to be more frequent and intense in future (BBC 2021). Also, electricity demand in South Asia is growing at a rapid pace, which is expected to continue in the future as well, with increasing energy access, electrification,

[1] India, Bangladesh, Bhutan, the Maldives, Nepal, and Sri Lanka are referred to as South Asian countries in this report.

and urbanization. These factors not only impact the magnitude but also the shape of the load curve (Joshi et al. 2021).

These trends have a direct impact on the reliability and resilience of the power system. Reliability includes operational reliability, which refers to the ability of a power system to provide supply despite sudden disturbances, and resource adequacy (NERC 2007), which is the ability of a power system to continuously supply power and energy to electricity consumers, considering various outages (NERC 2007). Having sufficient generation and transmission resources to meet peak demand and energy requirements does not necessarily mean the system is resource-adequate. The available generation resources should also be able to flex based on power system needs. This becomes more important with high renewable energy, where conventional generation is required to provide necessary flexibility to match the net load requirements. High-renewable energy power systems also need to manage associated challenges such as variability and inertia, which impact reliability and resource adequacy. This will also be relevant for South Asian countries like India, Bangladesh, and Sri Lanka (Fredrich Kahrl et al. 2021).

Resilience is the ability of the power system to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from extreme events (FERC 2021). The increasing frequency of extreme weather events in South Asia is testing the resilience of the power system. Events like cyclones can damage the transmission/distribution infrastructure and impact generation. Floods or excessive rains, leading to waterlogging, can damage transmission towers, make substations inoperable, and impact fuel availability. Earthquakes can also damage transmission/distribution infrastructure and cause generation outages. Drought and high temperatures can impact the system from both sides, causing higher electricity demand, less generation from hydro, and making some thermal generation unavailable due to lack of a cooling water supply. Power system planning and operations generally cover high-probability credible contingencies, but in some cases, planning excludes extreme weather events, which may have been considered low-probability events but whose probability and impact is being reconsidered in many electricity systems around the world (MISO 2019; PJM 2020; NERC 2007; PJM n.d.).

Collectively, reliability, resource adequacy, and resilience can be referred to as the three Rs of the power system. The changing resource mix and other factors mentioned previously make it important to adopt a holistic approach toward power system planning and operation, thereby ensuring the success of the three Rs. This would require the capabilities to perform integrated resource planning, involving many sectors (buildings, industry, transportation, etc.), intersectoral coordination, changes in standards and regulations, new data sets and tools for power system analysis, and innovative market products to support power system reliability. Improving power system resilience would require detailed planning, advance information about extreme events, risk assessment, emergency preparedness, and other related concepts.

With the objective to better understand the needs of South Asian power systems to ensure the success of the three Rs of future power systems, the South Asian Group for Energy (SAGE) undertook a project to identify pathways for research, modeling, and implementation in South Asia. SAGE is a consortium comprising the U.S. Agency for International Development (USAID), the U.S. Department of Energy (DOE), and three national laboratories: the Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory (NREL), and the Pacific Northwest National Laboratory. This project has three separate parts, one led by each lab, with several overlapping themes. NREL led the segment on the reliability and resilience of South Asian power systems, Lawrence Berkeley National Laboratory led the segment on electricity demand, and Pacific Northwest National Laboratory led the segment on power supply and climate impacts. This work focused on defining the emerging challenges to reliability and resilience in the region, understanding stakeholders' perspectives on these challenges, and identifying measures to tackle these challenges. The project team held virtual consultations with key stakeholders during October and November 2021, and feedback questionnaires were sent out to key stakeholders. The questionnaire responses are in Appendix A. This report is divided into country-specific sections discussing the results of our research on future challenges, stakeholder consultation, and present pathways for research, modeling, and implementation that will guide SAGE activities in the future.

2. India

The Indian power system is growing at a rapid pace, with around 6%–7% electricity demand compound annual growth rate (CAGR) over the last 10 years (MOP 2021), which is expected to grow at a similar rate in the future (CEA 2017). Major factors driving the demand in the future would be an increase in electricity access, appliance ownership, electrification of industries, buildings, electric vehicles, and climate patterns. Electrification in particular has the potential to alter this trajectory, as much of this would be new types of loads, and the rate of electrification is uncertain and likely to be driven by national or subnational policies and global trends. These factors would also impact the shape of the load curve and might make it more uncertain.

The major portion of electricity demand is currently met through coal generation, which contributes around 53% toward total installed capacity and close to 80% toward total generation in 2019–20. The other sources of generation are hydro, renewable energy, nuclear, and gas (CEA 2020). There is a strong push in the country to integrate a greater quantum of renewable energy resources with targets to achieve 175 GW by 2022 and 450 GW by 2030. This has resulted in an increase in renewable energy capacity, which crossed the 100-GW mark in August 2021. In a study focused on energy storage, NREL found the potential for continued growth in the capacity of wind and solar (~1,730 GW) by 2050 (Chernyakhovskiy et al. 2021). The Indian power system is also witnessing efforts by the Government of India to add energy storage to the power system (PIB 2021a). The Central Electricity Authority (CEA), which is responsible for power system planning in the country, also projects around 27 GW/108 GWh battery energy storage by 2030, in addition to pumped hydro capacity of 10 GW (CEA 2020). Green hydrogen could also play an important role in India, with the Government of India's ambition to become a global hub for green hydrogen production and export through national hydrogen mission (PVMI 2021). These factors will change the composition of India's power system in a future with greater uncertainties and more sectoral linkages, which requires a different perspective to ensure power system reliability.

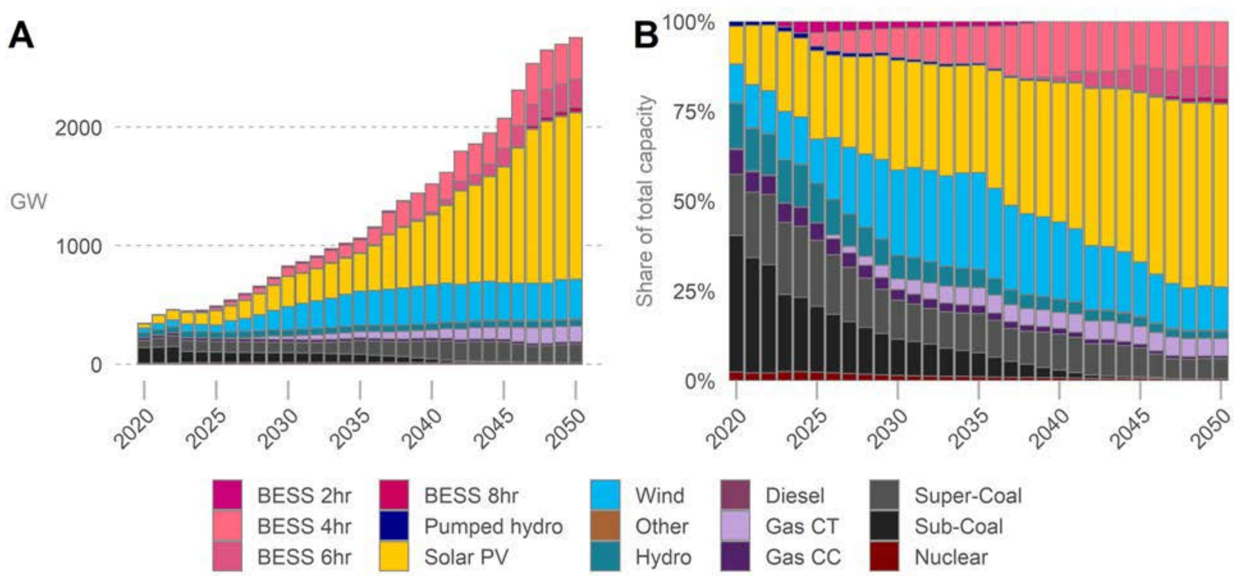

Figure 1. Projected installed capacity (A) and capacity mix (B) for India until 2050

Source: (Chernyakhovskiy et al. 2021)

The Indian power system is also susceptible to the impact of extreme weather events. India is ranked twentieth by the German Watch Climate Risk Index on the list of countries affected by climate change from 2000–2019 (Eckstein, Kunzel, and Schafer 2021). The country has seen several cyclones, floods, earthquakes, drought, heat waves, and other natural events that have impacted the power system (Soonee et al. 2018). Cyclones like Pahilin (2013), Hudhud (2014), Vardah (2016), Amphan (2020), Tauktae (2021), and more have directly impacted the reliable operation of the power system. A recent study by the Indian Institute of Tropical Meteorology indicates an increase of 52% in the frequency of cyclones over the Arabian Sea in last two decades (MINT 2021). Indian states on the east and west coast like Odisha, Maharashtra, Gujarat, Tamil Nadu, Karnataka, and West Bengal are often hit directly by these cyclones. Interestingly, some of these states are renewable energy-rich states, and such cyclones may have greater impact on the resource adequacy and reliability of systems with high renewable energy penetration. Also, 40% of thermal power plants in India are in areas facing high water stress (Luo 2018). Fourteen of India's twenty largest thermal plants experienced at least one shutdown due to a water shortage between 2013–2016, and around 14 TWh of thermal generation was lost due to these outages (Luo 2018). Excessive rains, causing floods, also impact the system. Additionally, the country faces fuel supply issues, especially during the monsoon period, when flooding in coal mines causes disruption in coal supplies (Sudarshan and Dash 2019).

Generation planning at the national level is the responsibility of the CEA, whereas transmission planning for the interregional and transnational transmission system is done by the CEA in coordination with the Central Transmission Utility (GOI 2003). The National Electricity Plan (in two volumes), covering the generation and transmission plans, is prepared by the CEA every 5 years. The approach to generation planning in the National Electricity Plan is to meet peak demand and energy for different seasons (CEA 2018). The CEA also published a study on optimal generation capacity mix for 2029–2030 in January 2020 (CEA 2020). The general approach of this study was similar to the National Electricity Plan, except for a few additional scenarios related to demand uncertainties, changes in battery cost and sensitivity analysis of renewable energy, and hydro reduction studied in the optimal generation mix study. The transmission planning is based on power flow studies conducted for different seasons and for different times of the day like peak, off-peak, noon-high wind, noon-low wind, and evening high wind. Generation and transmission planning exercises are done independently (CEA 2019).

Advancements in computing and power system modeling have opened the door to more interlinked planning between transmission and generation (Reiko Matsuda-Dunn et al. 2020; MISO 2021; Yinong Sun et al. 2021). And the higher penetration of renewable energy and energy storage, generation uncertainties either due to climate change or fuel supplies, and demand uncertainties make these investments potentially even more important to consider in one co-optimized process, when possible. The planning studies from the CEA also consider 5% of installed capacity for spinning reserve margin, a loss of load probability target of 0.2%, and an energy not served target of 0.05%. Reserve margin criteria, loss of load probability (LOLP), and energy not served (ENS) targets will be important to continually update, considering the increasing electrification and expectations of consumers for reliable round-the-clock power. Also, more detailed analysis could help to understand the periods during which the system is close to its limits for reserve margin, higher LOLP and ENS times. Inserting contingencies into these high-risk periods, such as fuel supply challenges or extreme events, could help to redefine periods of stress on the system as the power system transitions to higher levels of clean energy.

Hydro generation in the National Electricity Plan is considered based on the designed energy of the project in a 90% dependable year. On the other hand, hydro generation in the CEA's optimal capacity mix study was considered based on hydro generation patterns for last 3 years, with an additional sensitivity of reducing hydro generation by 6% during the peak demand week. renewable energy generation sensitivity is also studied in a similar way by reducing renewable energy generation during the peak demand week. While this may encompass a worst-case scenario, there are likely ways to improve this by using weather models and spatially detailed renewable energy data, which could lead to more cost-effective solutions. Climate change may also impact these resources differently, and a more detailed analysis could help capture river basin-specific analysis for hydro generation and the impact of different weather patterns on renewable energy generation. Similarly, the National Electricity Plan considers uncertainty in demand by analyzing scenarios with different CAGR, whereas the CEA study on optimal capacity mix considers scenarios with an increase and decrease in demand with reference to the base. Although efforts are being made by the CEA to project a most probable load curve for the future, additional input from other industries planning practices may help to account for increasing electrification in industry and buildings, energy efficiency, demand shifting, new appliances, and other similar factors in load curve projections.

Analysis of the impact of extreme events like cyclones, droughts, heatwaves, excessive rains, and floods on the power system in India will increase in importance in the future, as more aspects of the power sector are impacted by weather. A deeper and more detailed analysis of the potential risks of these events could help plan for and better manage these situations. This will require site-specific analysis, spatially and temporally granular data, and new tools for analysis. A potential model for this—merging the current planning frameworks with an additional resilience perspective—is integrated resource and resilience planning (IRRP), where extreme events analysis is also integrated with generation and transmission planning.

We met with the Indian stakeholders in a virtual meeting on October 25, 2021, to collect feedback on the emerging challenges and areas in which more work is required to ensure a reliable and resilient power system. The meeting was attended by the officials from Niti Aayog, the CEA, Central Electricity Regulatory Commission, National Institute of Wind Energy, National Institute of Bio Energy, and BSES Rajdhani. A summary of important areas highlighted by various stakeholders where more work is required are discussed below:

1. **Adaptation of planning philosophy to align with emerging challenges and needs:** Changing the power system would require planning exercises to answer some emerging questions. Some of the questions identified by the stakeholders during the meeting were:

    - How should planning keep pace with swiftly changing technologies and improve the shelf life of long-term plans?
    - How to incorporate emerging technologies in planning?
    - How will the swiftly changing technology impact existing assets? How can existing assets be used with the addition of new technology?
    - How to incorporate behavioral changes like changing electric vehicle charging patterns in planning studies?
    - How to make electricity more affordable with clean energy and emerging technologies by using the benefit of diversity in the country?

2. **Computational resources for planning simulations:** Power system planning is becoming more complex with the growth of power systems. The addition of renewable energy, which not only adds more constraints in modeling but also a greater number of small-sized plants and intersectoral linkages, additional constraints due to fuel shortages and the study of more time periods of importance presents challenges. This would require the development of new tools and techniques or deployment of better computational resources to improve the runtime of these simulations.

3. **Quality data for planning:** Any study is as good as its input data. Stakeholders feel a need for improving the input data quality for planning studies, especially considering the changing generation mix, climate change, and other emerging challenges. This would include electricity demand (energy and shape) forecasts, renewable energy potential and profiles, and climate change impact scenarios for renewable energy and hydro and other related inputs.

4. **Coordination between central and state planning agencies:** Power system planning in India is done by central planning agencies and state planning agencies. Stakeholders have expressed a need for

greater coordination between these agencies for efficient power system planning. This might require forums for all power system planners across the country, as well as a common model, tools for planning, and platforms for information sharing.

5. **Integrated resource and resilience planning:** As mentioned previously, extreme events have become more frequent and more intense in recent years (Mohanty 2020). renewable energy generation, which is expected to be major source of generation, is potentially more sensitive to these events. So far, these events are not holistically considered in power system planning. Stakeholders have expressed the need to integrate resilience planning with resource planning and study these events in detail to understand their impact on the power system and develop strategies to withstand these events and recover.
6. **Resource adequacy:** Stakeholders have expressed a need for more work in resource adequacy, which is becoming increasingly important with the various new uncertainties in the system. The changing resource mix, with the rapid growth in renewable energy (which is more variable and uncertain than a fossil-based resource) is the primary driver for increasing resource adequacy considerations. Additionally, fuel (coal and gas) supply issues may flare up in the future due to the uncertainties in hydro generation (including import from Nepal and Bhutan), renewable energy generation, and demand caused by climate change. Resource adequacy assessments need to be done at various levels to understand the periods in which resources are either inadequate or close to the margin, and make plans to improve this. Tools, data, and planning processes to utilize these resources effectively must be developed for resource adequacy assessments, incorporating various uncertainties in generation and demand.
7. **Probabilistic renewable energy forecasting**: Renewable energy forecasting is well established in India and around the world. Better integrating forecasting into operational practices and considering this process in planning will be important as these resources become a larger part of the grid. Additionally, the impact of climate change on weather forecasting also needs to be studied. This might require renewable energy forecasting to move from deterministic to probabilistic. Renewable energy generation forecasts for various probabilities would be helpful in better managing the power system.
8. **Cybersecurity:** Power systems around the world are facing the emerging threat of cyberattacks. This area is also important for Indian stakeholders, because cyber-related incidents have been reported recently in the power system (CEA 2021). This would require strategies and a plan to make power systems more resilient against such attacks, which includes risk assessment, mitigation plan, assets testing, and periodic audits. More work is required in these areas to develop in-house capabilities within each electric utility in the country.

3. Bangladesh

Bangladesh's power system is also growing rapidly, with a CAGR of around 9% in energy consumption, 11% in peak demand served, and 13% in generation capacity since 2009 (BPDB 2020; 2011). In Fiscal Year2019, Bangladesh consumed 71,419 GWh of energy and met a peak demand of 13 GW from 20 GW of generation capacity. The Power System Master Plan of Bangladesh projects a similar growth trajectory in the future, with 72 GW of peak demand and 79.5 GW of generation capacity by 2041 (MPEMR 2018). Energy access has also increased to 95%, with a government ambition to provide access to all by 2021 (SARI 2020; BPDB 2020). The reliability of the system is also improving gradually, with only 48 hours of interruption in the grid as compared to 136 hours in 2011 (BPDB 2020; 2011). The generation mix is dominated by gas generation, which contributes around 54% toward total capacity and 72% toward total energy. The other significant sources of energy generation are furnace oil (13.25%) and imports from India (9%) (BPDB 2020). Although the previous plan was to shift toward coal-based generation in the future as domestic gas fields were depleted, the central government is now pushing to expand renewable resources and interconnection with neighboring countries (ITA 2021). Under the recently published draft solar energy action plan, the country is projecting 40 GW by 2041 under the most ambitious scenario or 25 GW under the medium scenario (Chowdhury 2020).

Bangladesh also faces challenges due to extreme weather like other South Asian countries. The country is ranked seventh by the German Watch Climate Risk Index on the list of countries affected by climate change from 2000–2019, with 185 extreme events and regular experiences of flooding and cyclones (Eckstein, Kunzel, and Schafer 2021). Bangladesh experienced its worst-ever blackout in 2007 after the impact of severe Tropical Storm SIDR. It took a couple of days to restore the power supply (Shahid 2012). Floods have also interrupted power supplies over the years, and severity has increased in the past few years. The floods of 1988 caused the flooding of eighteen substations, leading to the de-energization of 2,000 km of 11-kV power lines (Shahid 2012). Record floods in 2020 also threatened the progress of the Rooppur nuclear power plant (Femia and Werrell 2020). Ironically, the same power plant also faces challenges due to water shortages (TTP 2015). Environmental and climate change concerns make it challenging to site new generation and operate existing or planned generation reliably.

The Power System Master Plan was published by the Power Division of the Ministry of Power, Energy and Mineral Resources. The latest version of this plan was published in 2016 with support from the Japan International Cooperation Agency, which was later revisited in 2018. Generation planning is based on a least-cost approach with detailed projections for various aspects of the power system, like demand, fuel price, fuel availability to meet peak, energy requirements within reliability, and reserve margin criteria (MPEMR 2018). Transmission planning is done after generation planning, through steady and dynamic power flow studies for various scenarios in different years. Areas of importance for ensuring reliability and resilience of Bangladesh's power system are similar to India's, such as power system planning, renewable energy forecasting, extreme events, etc. Additionally, the grid is changing rapidly with ambitions for increasing renewable energy. Because Bangladesh is at the starting phase of the renewable energy revolution, it is important to set things right from the start to ensure a reliable and resilient power system in the future. This would require putting necessary regulations, standards, and mechanisms in place for forecasting, scheduling, imbalance handling, frequency control, reserves, resource adequacy, planning, and infrastructure design, with due consideration for extreme weather. We approached stakeholders with this background of emerging challenges and needs of the system to understand their perspectives and views.

A virtual meeting was held on November 2, 2021, with stakeholders from Bangladesh to collect feedback on the emerging challenges and areas where more work is required to ensure a reliable and resilient power system. The meeting was attended by the officials from the Power Grid Corporation of Bangladesh, Bangladesh Power Development Board, Dhaka Electricity Supply Company, Dhaka Power Distribution

Company, USAID Bangladesh, Sustainable and Renewable Energy Development Authority, and Centre for Policy Dialogue. A summary of important points highlighted by various stakeholders are discussed below:

1. **Quality data for planning and operations:** Stakeholders in Bangladesh need better data to improve planning and operations. This includes better load forecasts, site-specific climate change impacts, renewable energy data, and archival of historical data such as outage statistics and operating parameters for other data inputs.
2. **Resource adequacy:** As mentioned before, the generation mix in Bangladesh is dominated by gas, followed by furnace oil, diesel, then coal. Essentially, there is a dependence on fossil fuels, some of which must be imported. Depleting gas reserves in the country would put more reliance on imported fuels, which is subject to availability and price volatility. This resource mix is a matter of concern for stakeholders, and ensuring resource adequacy is a challenge. The addition of solar capacity in the future would add variability to the system, which will make resource adequacy even more important. Power system planning should consider these aspects and ensure resource adequacy under all scenarios. This might require new tools and techniques for resource adequacy assessments to complement the existing planning studies.
3. **Impact of extreme events on power system:** Stakeholders are concerned with the impact of extreme events like flooding, cyclones, and heatwaves on the power system. Flooding would be more important to consider in the future, with a greater share of solar generation occurring where the panels might get submerged in floodwater. Also, large-scale nuclear plants are planned in future; these are generally planned in low-lying areas near water sources, which means they face similar threats. Construction of future plants should specifically consider these dangers. The impact of higher temperatures or heat waves also impacts the operations of the power system in Bangladesh. Electricity demand has a direct relationship with temperature, and this relationship would be stronger in the future with the adoption of air conditioners and other electrical appliances. Thermal plant efficiency and operations are also adversely impacted by higher temperatures. Of course, the threat level of extreme events would be different at different sites. A more detailed site-specific analysis may be required to better understand these challenges, and the same analyses need to be incorporated at the planning and operational level.
4. **Cooperation between South Asian countries:** Stakeholders are of the opinion that cooperation between South Asian countries could be an important tool in ensuring reliability and resilience in the region. Harnessing the diversity of generation resources and electricity demand between the countries has the potential to reduce the cost of supply and improve system reliability and resilience. This would require mechanisms for sharing resources, coordinated planning and operations, and cooperation in crisis.
5. **Load forecasting:** Load is changing rapidly, and its forecasting is becoming challenging for planners, operators, and distribution companies. Emerging technologies such as electric vehicles and energy storage, along with climate change and the adoption of electrical appliances, would increase the uncertainty and add to this challenge. A bottom-up approach for load forecasting is needed, in the opinion of stakeholders.

4. Sri Lanka

The Sri Lankan power system is also undergoing a transformation, with increasing electricity demand and energy policies focused on sustainable infrastructure goals. The country's average electricity demand growth over the last 10 years is 4% with a maximum recorded peak of 2,717 MW. Sri Lanka expects around 5.6% average growth in energy and 5.4% in peak demand over the next 10 years. The total installed capacity of 4,615 MW generated 15,714 GWh in 2020 (CEB 2021). The generation capacity comprises 53% clean energy resources and 47% thermal power technologies. The clean energy resources comprise mostly large and small hydro and, to some extent, solar, wind, and biomass technologies. Multiple technologies of thermal power plants are operated using imported coal and oil fuel. Because all the power plants do not provide flexible power to the grid, the capacity mix is further categorized as 3,551 MW dispatchable or conventional capacity and 1,064 MW renewable energy capacity. The current power system provides 100% electricity accessibility to the nation, and the growing electricity load of multiple sectors and clean energy goals demand that new capacity be added to the grid.

The capacity expansion plan for Sri Lanka is prepared by the state-owned power utility, Ceylon Electricity Board. This plan investigates thermal and renewable technology options and connection to the Indian power grid to meet the forecasted load for 20 years while meeting sustainable energy policy goals (CEB 2021). Three probable future power grid scenarios indicate that the country is planning to achieve 50% renewable energy and 70% low carbon energy targets by the year 2030. Because most of the hydropower potential has been exploited in the country, the solar, wind, pumped storage, combined cycle, and combustion turbines operated by natural gas are planned to be added in the grid over the next 20 years (Figure 2). Solar and wind power are planned to be developed at both the utility scale as well as the distributed generation level (CEB 2021; CHN 2021).These planning studies also indicate that hourly net-load ramping will increase up to 25% of the peak load, and evening netload ramping will be increased to 50% of the peak load by the year 2041. In these plans, operating reserves are planned from the natural gas-operated combined cycle and combustion turbines and pumped hydropower plants.

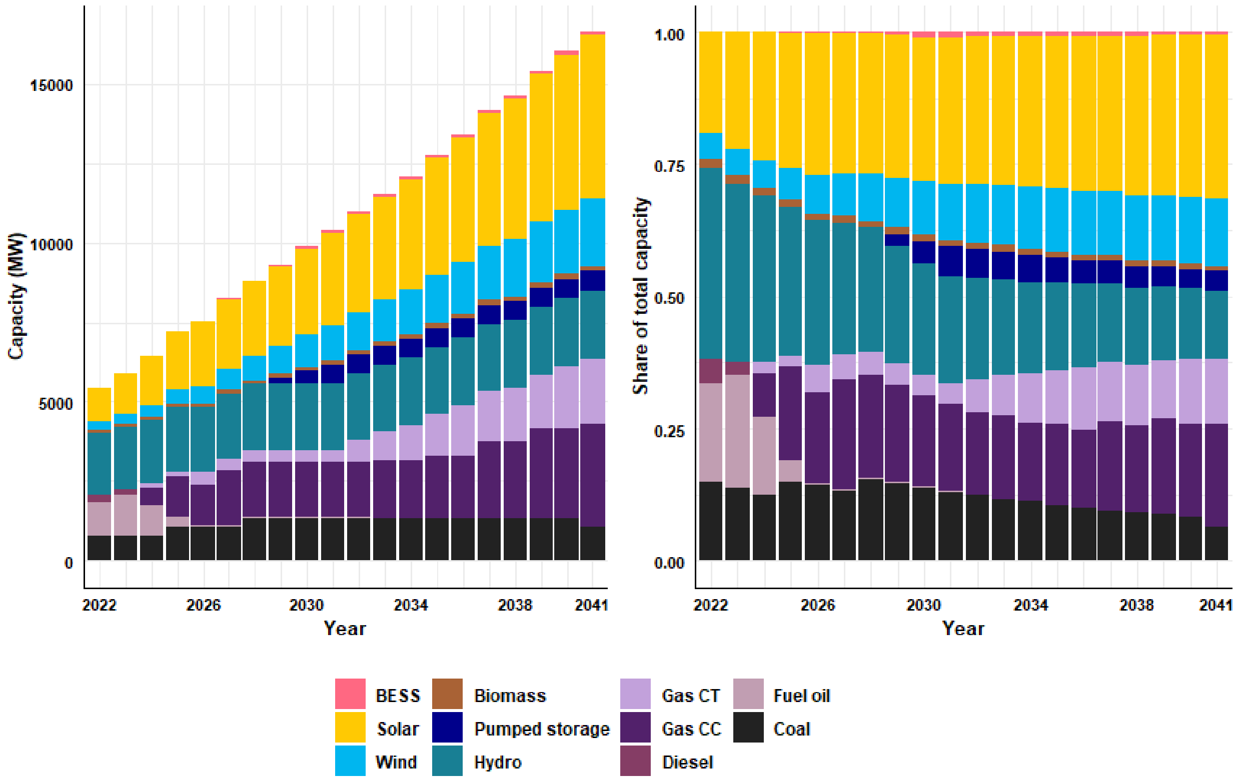

Figure 2. Projected installed capacity (left) and capacity mix (right) for Sri Lanka until 2050

Source: (CEB 2021)

The planned growth of renewable energy capacity and dependence on imported fossil fuels indicate a potential risk to the Sri Lankan power grid by extreme weather events. Although capacity expansion plans for the country do not provide details for the vulnerability of the power grid to climate and extreme weather events, several studies have identified the potential risk for the energy sector (MMDE 2016). The country is ranked thirtieth by the German Watch Climate Risk Index on the list of countries affected by climate change from 2000–2019 (GERMANWATCH 2021); nevertheless, changes in monsoon patterns and extreme weather impact the power grid and whole economy (WB 2018).

The Sri Lankan power grid is impacted by the variability of monsoon seasons, which occurs from May to June (Northwestern monsoon) and October to January (Northeastern monsoon) and other inter-monsoons. Hydropower, which is 40% of the total installed capacity, is built on two large reservoir cascades of two rivers and many other small hydro plants at several rivers, which depend on the monsoon rainfalls. Failure of monsoon rainfalls (also known as droughts) severely impact the continuous electricity supply and reliability of the grid (Repair 2019). The El Niño-Southern Oscillation and IOD teleconnections to the monsoons have been identified (De Silva M. and Hornberger 2019), and these atmospheric teleconnections are predicted to be severe with climate change (Cai et al. 2021). Studies show that there is a significant probability of a failing northeastern monsoon for the El Niño phase and higher precipitation for the La Niña phase. Furthermore, climate change may impact the intensity of monsoon rainfall, which can lead to droughts and floods because the current water resource planning infrastructure is not sufficiently able to handle the variability of monsoons. Failure of large storage hydropower plants can severely impact the high renewable energy grid, as large hydropower plants provide grid ancillary services for a lower cost. In addition, wind patterns for the country are also correlated to monsoons, and the variability and uncertainty of wind power generation increases with climate change. Therefore, power grid reliability, resilience, and resource adequacy assessments require the consideration of multiple weather years and future projection information.

A higher dependence on imported fossil fuels also decreases the reliability and resilience of the power grid. Currently, fossil fuel unloading for some ports is limited to 6 months due to the monsoon effect, which means the variability and uncertainty of the monsoon severely impacts the fossil fuel supply. In addition, extreme weather events such as cyclones also interrupt the supply of fossil fuels. Currently, the utility imposes power cuts during failures at a large coal plant due to high dependence on fossil fuel plants and insufficient reserve capacity (PTI 2020). It also becomes difficult for Sri Lanka to purchase fuel at a low price from the global market, due to small fuel quantity requirements. Grid reliability and resource adequacy is exposed to fossil fuel price variations, and this severely impacts the economy of country. For example, in 2017, the fossil fuel import cost was 15% of the total imports to the country (WB 2021). Utility planners forecast a 50% price increase for natural gas, which will be reflected as a 15% total system cost increase in the system plans (CEB 2021). Long delays in implementing the power projects also reduce power system reliability and resilience (Aneez 2019).

We met with USAID Sri Lanka and the team from Chemonics, who is implementing USAID's energy program in the country. Chemonics has done extensive consultations with various stakeholders in the country, and they have highlighted the following findings as important areas where more work is required to ensure a reliable and resilient power system:

1. Coordinated/integrated generation and transmission planning to identify optimum solutions to meet the policy and decarbonization targets
2. Technical solutions to improve resiliency with high renewable energy penetration
3. Technical solutions to support the integration higher levels of renewable generation (storage, demand response, interconnection with India, etc.) whilst preserving system resiliency
4. Impact of high penetration of distributed energy resources on protection schemes and power quality
5. Potential for emerging technologies to integrate renewables, support grid resilience, defer/avoid network upgrades, and provide grid services
6. Load modeling and forecasting
7. Assessment of electric vehicle adoptions and charging implications (public/private, fast chargers, etc.) on the power system
8. Review of regulations considering high renewable energy targets
9. Planning study to ascertain the requirements for flexible generation, transmission infrastructure, and grid support interventions, including capital investment to realize high renewable energy targets for 2030 envisaged by government
10. Assessment of demand response as a resource to support grid stability, integration of renewables, economic grid operations, and capital investment deferment/avoidance.

5. Nepal

Like other South Asian countries, Nepal's power system has also grown at a rapid pace in the last decade, with a CAGR of 6.37% in electricity consumption and 4.59% in peak electricity demand (NEA 2021; 2011). The country met a peak demand of 1,483 MW and consumed around 8,878 GWh of energy in 2021 (NEA 2021). Nepal is one of the fastest electrifying countries in the world, with annual rate of 4.3% and around 90% access to electricity (EEG 2021). The country also has ambitions to improve electrification, with 90% of new private passenger vehicles sales coming from electric vehicles and 25% of households using electric stoves by 2030. The electricity demand is expected to increase faster with an annual rate in the range of 10%–15% with energy consumption in the range of 66,006 GWh to 115,294 GWh under various scenarios by 2040 (WECS 2017). Nepal is entirely dependent on hydro generation to meet this growing demand. By 2030, the hydropower installed capacity is expected to increase from 1,400 MW at present to 15,000 MW (GON 2020). Most of the existing hydropower projects are run-of-river, and only a few have limited storage capacity.

Nepal is also vulnerable to the impact of climate change. The country has become warmer over the years, and precipitation has reduced. A 0.06°C rise in temperature annually was observed between 1975 and 2005, as well as around a 3.2% reduction in precipitation per month per decade (GON 2016). The mean temperature is projected to increase 1.3°–3.8°C by the 2060 and 1.8°–5.8°C by 2090 under various climate change scenarios (GON 2016). This would directly impact the electricity demand and hydro generation. Annual precipitation is also projected to be less and more uncertain. During the winter season of 2019–20, the accumulated rainfall was around 240% of normal, while at the same time in 2020–21 it was only 25% of normal (NEA 2021). Also, most of the power plants were closed due to flooding caused by excessive rainfall in mid-June 2021 (NEA 2021). There are also instances of transmission tower damage caused by flood, leading to disruption in power supply or evacuation of hydropower (NEA 2021). A study conducted by the Climate & Development Knowledge Network for the Government of Nepal assessed the impact of climate change on hydro generation in the country. The study concluded that climate change will have a widespread impact on hydro generation in Nepal, with higher variability, seasonal, and interannular variations in water inflows, especially with run-of-river hydro. Sediments, floods, and geological hazards like glacial lake outburst floods and landslide-induced dam outburst floods are also likely to impact hydro generation in the future (CDKN 2017).

Uncertainty and variability of hydro generation is likely to be the most important factor impacting the reliability and resilience of Nepal's power system in the future. This might be more significant in the future with climate change and more run-of-river hydro generation. This would require a detailed assessment of the climate change impact on each hydro plant or river basin. An integrated planning approach, incorporating water availability, generation, transmission, climate change, and sectors impacting the electricity demand would be needed to improve reliability and resilience. Coordinated planning and operation with India and other South Asian countries would also be beneficial to mitigating the impact of climate change and extreme events on the power system.

A virtual meeting was held with the officials from the Nepal Electricity Authority and Ministry of Energy and Water Resources and Irrigation on November 30, 2021. We discussed their perspective regarding the existing and future challenges to reliable and resilient power system in Nepal. Important areas identified by the stakeholders are discussed below.

1. **Limited flexibility in generation mix**: All the stakeholders expressed concerns regarding the challenges posed by the generation mix dominated by run-of-river hydro generation. With only limited ability to store water, they have excess generation during the summer/monsoon months and less generation during winter months. Although Nepal is planning for some storage-based

hydro in future, they will continue to depend upon India for balancing this supply excess and deficit. High silting is also observed in some months, causing generation limitation or outages.

2. **Impact of climate change**: The problem of limited generation flexibility is further accentuated by the impacts of climate change, which leads to record-high rainfalls during monsoons and drought conditions in winter months. High rainfalls are also causing floods, impacting generation and transmission. Stakeholders are also concerned about glacial lake outburst floods, for which they do continuous monitoring. All these factors make resilience planning important, including data sets to include the impact of climate change on the power system.

3. **Load growth**: With 6,000 MW of power purchase agreements already signed with power plants in Nepal and around 9,000 MW generation in the application phase, Nepal is expected to be at a surplus in the future. However, demand is not growing at the same pace, which leaves Nepal no option but to export power to either India or Bangladesh. The first priority of Nepal's government is to increase demand by promoting induction cookstoves and electric vehicles. They are looking for support and guidance in improving internal demand.

6. Bhutan

Bhutan's power system is entirely based on hydro generation, with an estimated potential for 36.9 GW (MOEAB 2021). The country has an installed capacity of 2,335 MW at present to meet a peak load of 387 MW (BPSO 2020). Bhutan is connected synchronously with India, and excess hydro energy is exported to India. The peak load of the country has grown, with a CAGR of 7.8% since 2007 (BPSO 2020). The National Transmission Grid Master Plan 2018 envisions development of 16.6 GW of hydro generation by 2040 (MOEAB 2018). The existing hydro capacity is run-of-river with limited flexibility, and the future capacity is expected to be the same. The total energy demand of Bhutan is expected to be 6,404 MU, with a peak demand of 1,150MW by 2040 (MOEAB 2018). The Government of Bhutan has plans to develop four industrial estates, which are expected to contribute a great deal toward this increasing load apart from domestic load.

Extreme weather has the potential to impact the power system of Bhutan with intense monsoons, floods, and glacial lakes bursting in the summer, followed by lower water inflows in the winter season. Heavy monsoon rain on August 6, 2019, drenched the mountainside of the Punatsangchhu river, which led to the formation of an artificial lake; the artificial lake burst, causing sudden heavy water flow. These events have the potential to wipe out a hydro power plant, as was seen in India in August 2021, when a similar incident damaged a number of hydro power plants. Reliability of the power system in Bhutan is also impacted by lightning strikes, which contributes to many power outages (Tshering et al. 2015). There are instances of complete power plant outage due to these events (TB 2019).

Reliability and resilience of the power system in Bhutan is not only important from the perspective of power, but also from the perspective of the economy. Hydropower contributes 14% of gross domestic product and 26% of the annual revenue (Rinzin 2017). It is therefore important to model and analyze the impact of extreme weather on hydropower. Because Bhutan is synchronously connected with India and dependent on it for absorbing the excess hydro power, developments in India would also impact Bhutan. A coordinated approach toward planning and resilience with India is important for Bhutan, considering various uncertainties and climate impacts in both countries.

7. The Maldives

The Maldives comprises many islands in the Indian Ocean, and each island has its own power system with no interconnection, effectively a minigrid with a diesel-based generation system. The total installed capacity in the Maldives is around 530 MW, with diesel generation of 319 MW in inhabited islands and 210 MW in resorts (MEA 2020). The greater Malé region accounts for 58% of electricity generation, and the other 42% comes from outer islands (MEA 2020). Energy demand in the Maldives has grown many fold in the last few decades, with growth in tourism, fishery industry, sea transport, and construction (ADB 2020). Total electricity consumption in 2019 was around 750 GWh (MEA 2020).

80% of the land area in the Maldives lies within one meter of sea level. Increasing sea levels due to climate change are a threat to the existence of many islands in the country. Understanding this challenge, the Maldives committed in December 2015 to reduce greenhouse gas emission by 10% of its business as usual by 2030. Recently this target was updated to 26% (conditional) by 2030 compared to business as usual and net zero by 2030. Adoption of renewable energy is at the forefront of this ambition, with plans to achieve 15% share of renewable energy capacity with energy storage (MOEM 2020). Diesel generation in the greater Malé region could also be replaced with liquefied natural gas-based generation in nearby Thilafushi island and network interconnection.

The Maldives has altogether different sets of power system challenges than other South Asian countries. The reliability and resilience of island power systems will be important for the country as it moves toward higher penetrations of renewable energy. The country is already impacted by extreme climate change-related events, which might be more frequent and intense in future. These factors require detailed planning, incorporating the variability of renewable energy, the changing climate, and the impact of extreme weather, which could be possible with better tools and data sets.

8. Pathways for Research, Modeling, and Implementation

South Asian countries are transforming their power systems by improving electricity access, increasing electrification, and providing a round-the-clock reliable power supply primarily from clean energy resources. This transformation poses challenges to the reliability and resilience of the grid. As the dependence on electricity increases, planners and system operators would be required to ensure an even greater level of reliability even under extreme scenarios. At the same time, the future generation mix comprising primarily solar, wind, and hydro would be more variable and uncertain in comparison to thermal generation. All these challenges would be accentuated with climate change and extreme weather events. This opens pathways for the research and development of solutions to meet the challenges of the future grid. Based on our discussions with the stakeholders in South Asia, the following pathways have been identified in which SAGE would support South Asian countries in the future:

1. **Renewable energy data to support power system studies**: As mentioned before, quality data is the backbone of all power system studies. Planners, system operators, and other stakeholders often require various data sets, such as standard technical parameters, models, demand pattern, renewable energy generation profile, renewable energy technical potential, renewable energy levelized cost of energy, and other similar data. As the penetration of renewable energy increases in the grid, even more studies requiring renewable energy data would be undertaken by various utilities. renewable energy characteristics may be different for different locations and different for different years, even for the same location. This makes renewable energy assumptions based on representative data for a single year difficult. NREL, with support from USAID India, has already made available solar resource data from 2004 to 2019, wind data for 2014, and other renewable energy characteristics, such as technical potential and levelized cost of energy for South Asia, on the Renewable Energy (RE) Data Explorer tool. There is a need to continue to invest in improving and updating these data sets and expand the granular wind resource data for more years, which can help utilities in extreme event analysis and the impact assessment of different renewable energy profiles on reliability and resource adequacy. With climate change and more frequent extreme weather events, there is also a need for data sets to explore possible climate change scenarios and their impacts on clean energy resources such as hydro, solar, and wind.
2. **New tools and studies to support power system reliability and resilience:** Planners and system operators conduct various studies to ensure power system reliability and resilience. We found that these studies in South Asia are mostly limited to long-term planning and power flow analysis, with some exceptions. In some cases, even long-term planning studies are not being performed. As the penetration of renewable energy increases, it would be difficult to manage the grid without updating tools and analyses to integrate new realities. Furthermore, there is a need to do more analysis, such as production cost modeling, resource adequacy assessment, reliability assessment, extreme events analysis, and climate change impact assessment. Some of these requirements are discussed in detail below.

   Evolving power systems need evolving tools. It is important to ensure renewable energy and other emerging technologies are correctly represented in the tools used for various power system studies. For example:

   - Long-term planning studies would be required to incorporate increased temporal and geographical resolution, renewable energy variability, distributed energy resources, energy storage, electric vehicles, demand response, climate change impact, and technologies for deep decarbonization in the future. More work is needed to develop new tools that consider these needs.

- Assigning firm capacity contribution or capacity credits for renewable energy and emerging technologies is a more complex exercise than assigning values based on capacity factors. It has potential to alter the optimal generation mix. Probabilistic techniques with multiple renewable energy and load profiles might be better suited as they consider a wide range of possible operating states across many time steps to quantify the firm capacity contribution of renewable energy and emerging technologies.
- Intersectoral dependencies are expected to increase with electrification. Not only will more coordination be needed between many sectors, but these dependencies also need to be suitably modeled in planning and operations.

These emerging needs would require the development of new tools that can enable the modeling of various new technologies and many sectors in detail in the same studies. Open tools might be an option, as they are more adaptable for these needs and country-specific requirements. Also, as we keep adding complexities, models would require greater computational resources. New tools must be efficient in their utilization of computation resources, as every utility in the region may not have best available resources.

3. **Resilience planning:** Resilience might be the centerpiece of future grid planning, along with reliability, as extreme weather events impact the grid more frequently. Grids in South Asia need to be more resilient, with specific plans and investments in place to ensure this resilience. The first step in this direction would be to define a road map, outlining specific goals, desired outcomes, and activities to be taken over specified time frames to increase grid resilience. This document will also guide governments and stakeholders to effectively convene for adaptable and holistic planning. Policies, regulations, standards, and procedures need to be amended with resilience-specific clauses in construction, planning, and operations. The traditional integrated resource planning process also needs to include resilience planning, which is different from the disaster management plan widely used in the region. Detailed analysis of extreme weather events would also be needed, as the consequences of such events could be much greater than in the past, and the time available to react would be much shorter. More research is required to develop tools, data sets, and resilience-based metrics to support utilities in achieving this objective.
4. **Resource adequacy:** With many sectors depending more and more on electricity in the future and the higher economic impacts of outages, even greater levels of grid reliability and resilience will be required. Resource adequacy will be increasingly important but also much more difficult to accurately quantify in a grid with higher levels of variable and energy-limited resources, decreasing levels of dispatchable generation, frequent extreme events, and higher levels of correlation between load and temperature. Traditional techniques ensuring resource adequacy by meeting traditional daily energy and peak demand might not be sufficient as risk shifts away from peak demand periods to different times of the day and year, and energy-limited resources such as storage introduce new intertemporal dependencies that further complicate considerations. New tools, techniques, and data for resource adequacy assessment would be required to model emerging technologies and the associated uncertainty and variability of generation and demand. Consumer ability and willingness to shed load would also need to be captured in these assessments. More research is required to evaluate whether the existing average-based resource adequacy metrics like loss of load expectation and expected unserved energy are sufficient or new metrics should be developed (potentially quantifying the severity of tail events), given increasing correlations in availability of the changing resource mix and the need to plan for extreme weather.
5. **Advanced renewable energy forecasting capabilities:** Renewable energy forecasting techniques are the basic building blocks of clean energy transitions. System operators and utilities depend upon these forecasts for operations and power purchasing. Higher forecast errors cause imbalances in the grid, which impacts its reliable operation. The South Asian region needs to

improve both long-term and short-term renewable energy forecasting techniques, which will enable utilities to operate the grid more reliably. More research is also needed to understand how climate change will impact these forecasts and what techniques can be useful to further improving forecasts.

6. **Cybersecurity:** Power systems are not only impacted by internal factors but also by external factors such as cyberattacks. This is an area of growing concern for electric utilities in the region and around the world, driven by multiple trends. One is the malicious intent demonstrated by cybercriminals and nation-state actors targeting critical infrastructure. Another is the increase of renewable energy as a percentage of overall generation. This shift to renewables will change the electric grid's attack surface (i.e., the cyber-connected aspects of the grid that are susceptible to cyberattack) and require more research focused on how best to secure this critical infrastructure. The future grid must be resistant to cyberattacks, and suitable measures need to be in place to ensure continuity of operations in the event of an attack. This includes a process for conducting cybersecurity assessments based on highly regarded industry frameworks; system security analysis (including energy system network emulation); encryption platforms for securing remote solar installations; and cyber-governance improvement tools. Security challenges faced by utilities need to be studied, as they deploy renewable energy solutions and can develop solutions specific to the needs of South Asian systems.

7. **Load forecasting:** Increasing access to electricity and the thrust toward electrification in South Asia might completely change load characteristics in the future. New appliances, industries, buildings, transportation, and other factors have the potential to not only change the magnitude but also the shape of load curves and add new uncertainties. More sectors will have significant contributions toward load, which would require greater intersectoral coordination. A greater percentage of load might be sensitive to temperature, causing challenges during heatwaves. More electrification also presents opportunities for greater demand-side flexibility, which will further impact the load curve. These factors have the potential to change the optimal generation mix for the future and need to be correctly factored into the long-term planning. A more bottom-up approach might be needed in the future, requiring more research to develop tools and mechanisms factoring in the various associated uncertainties.

8. **Coordinated planning and operations in South Asia:** South Asian countries are working gradually to improve the reliability and resilience of their power system. However, greater coordination and cooperation between these countries could further improve reliability and resilience—and at a much lower cost. Countries can take benefits from the diverse resources and demand patterns across the region. Coordinated planning and greater interconnection can help in optimizing the generation resources, which will not only save money, but also reduce emissions. Cross-border interconnections may also be justified from the perspective of improved resilience. It is unlikely that all countries will be impacted by outages, shortages, and extreme events at the same time, so coordinated operations and improved coordination during crises can improve reliability and resilience throughout the region. More work is needed to first demonstrate the benefits of coordination and cooperation between South Asian countries and then develop models, tools, and mechanisms to support this objective.

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Appendix A. Summary of Feedback Questionnaire Responses

A feedback questionnaire was shared with key stakeholders in South Asia to understand the challenges to reliability and resilience of the future power system and also areas where more work is needed. This questionnaire included questions related to reliability, resilience, resource adequacy, climate change, and load forecasting. A summary of responses received from the stakeholders for the questions related to reliability, resilience, and resource adequacy is given below.

1. Which of the following challenges are you most concerned about having an impact on the operational reliability of the power system in the future?

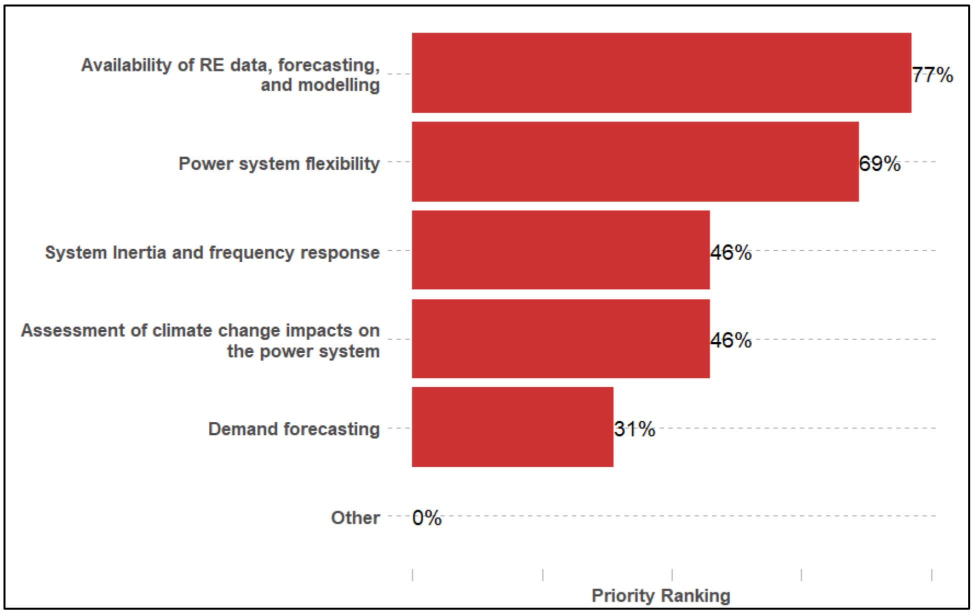

Figure A-1. Priority ranking of operational reliability challenges for South Asian power systems in the future

2. Which of the following challenges are you most concerned about having an impact on the resource adequacy of the power system in the future?

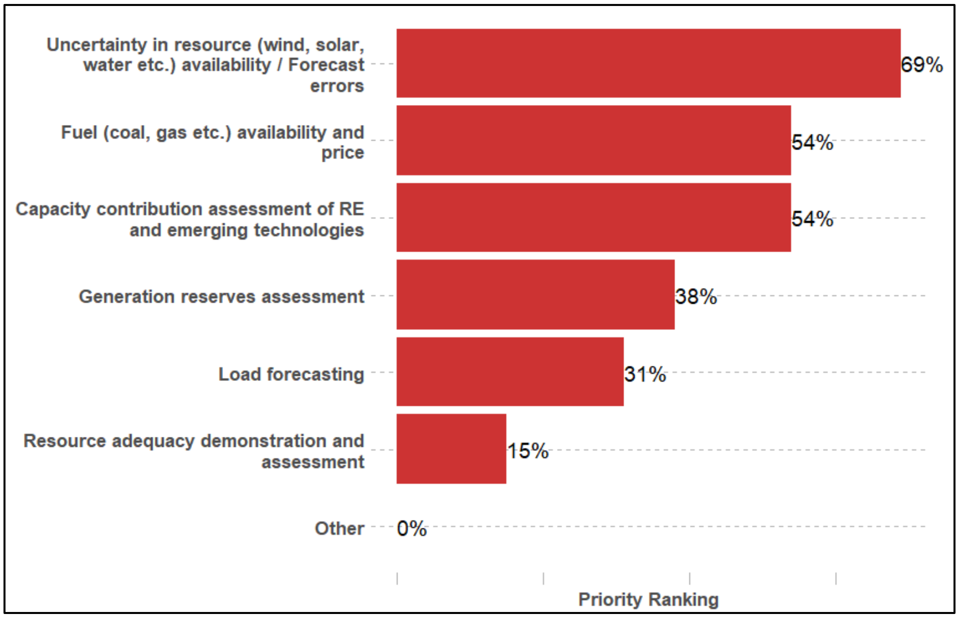

Figure A-2. Priority ranking of resource adequacy challenges for South Asian power systems in the future

3. Which of the following challenges are you most concerned about having an impact on the resilience of the power system in the future?

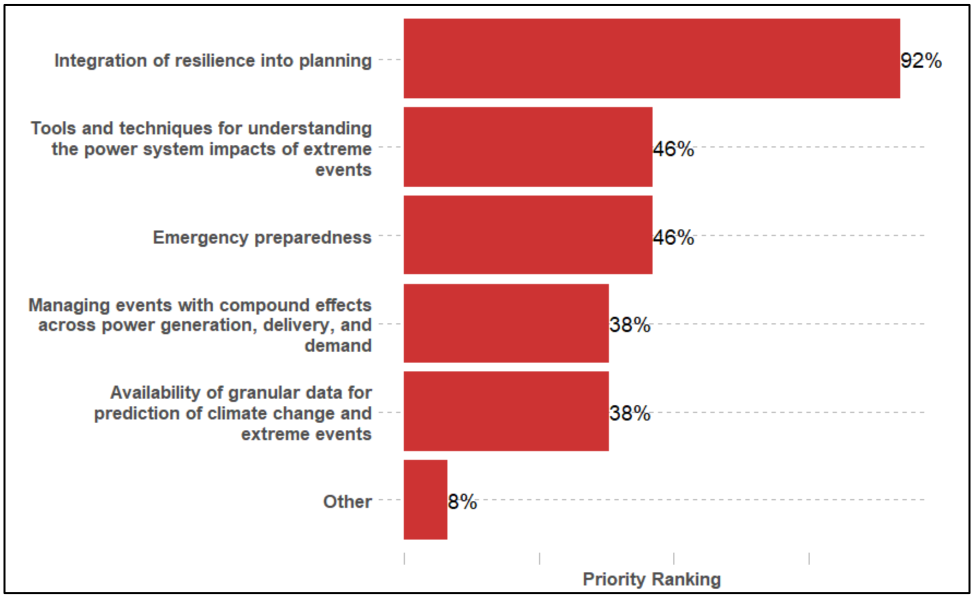

Figure A-3. Priority ranking of resilience challenges for South Asian power systems in the future

4. Which of the following challenges are you most concerned about having an impact on power sector planning in the future?

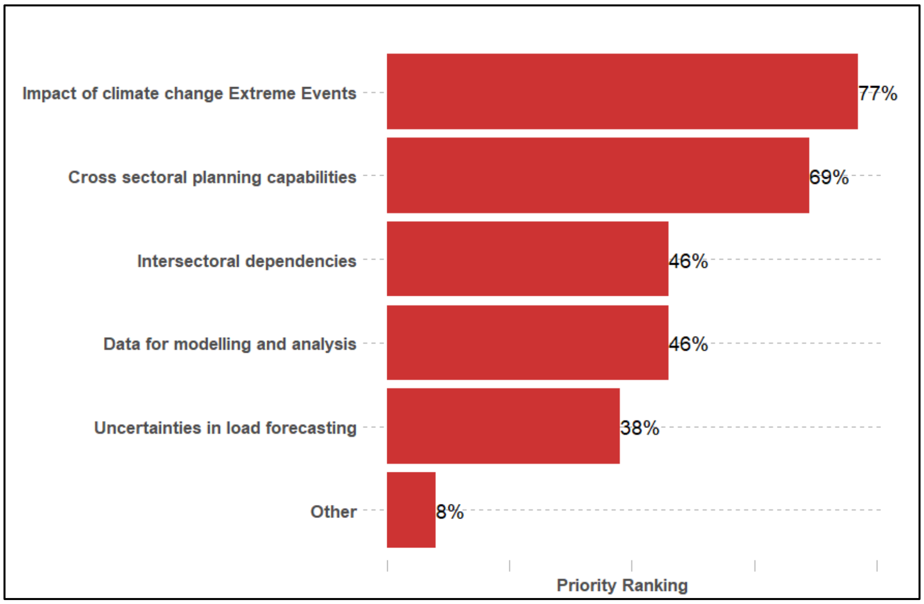

Figure A-4. Priority ranking of power system planning challenges for South Asian power systems in the future

5. Where do you think more work is required to ensure the reliability and resilience of the power system in the future?

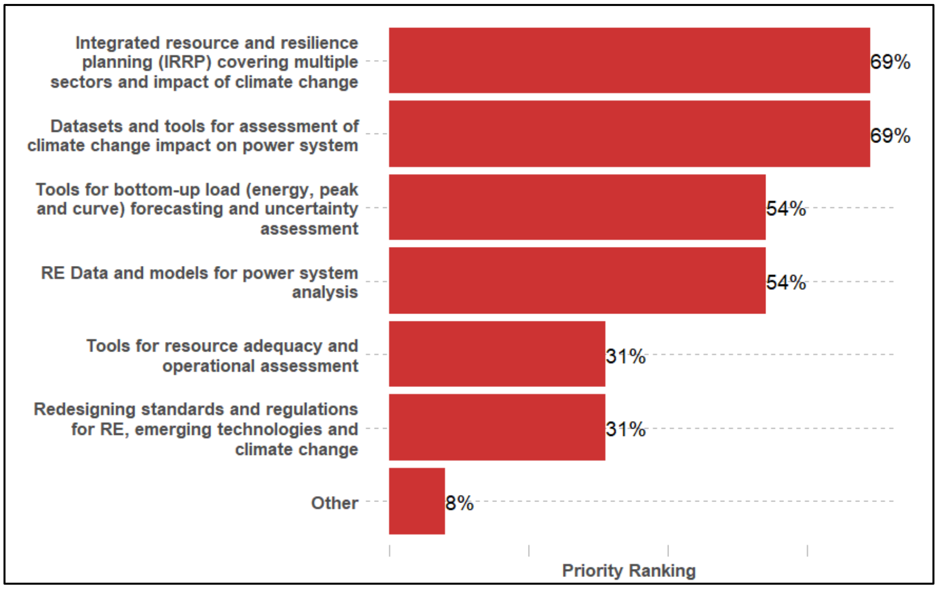

Figure A-5. Priority ranking of areas where more work is needed to ensure reliability and resilience of the South Asian power systems in the future

Note:

1. The response given under option "Other" in Figure A-3 and Figure A-4 was cost and financial resilience.

2. The responses given under option "Other" in Figure A-5 were pilots/technology demonstrations to mainstream islanding capabilities and cost and financial resilience.

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