Role of Renewable Energy, Storage, and Demand Response in Karnataka's Power Sector Future

Prateek Joshi, Amy Rose, Ilya Chernyakhovskiy

National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-83463
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Suggested Citation

Joshi, Prateek, Amy Rose, and Ilya Chernyakhovskiy. 2022. *Role of Renewable Energy, Storage, and Demand Response in Karnataka's Power Sector Future*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-83463. https://www.nrel.gov/docs/fy22osti/83463.pdf.

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Preface

This report is part of a broader program focused on supporting Indian states with long-term power system planning. More information about this program can be found at the National Renewable Energy Laboratory's "Supporting India's States With Renewable Energy Integration" web page at https://www.nrel.gov/international/india-renewable-energy-integration.html.

Other publications in this series include:

- *Pathways for Tamil Nadu's Electric Power Sector: 2020 - 2030* (Rose et al. 2021)
- *Opportunities for Hybrid Wind and Solar PV Plants in India* (Schwarz et al. 2022)
- *How to Conduct a Long-Term Planning Study: Guidelines for Power System Planners* (NREL 2021)
- *Power System Planning: Advancements in Capacity Expansion Modeling* (NREL 2021)
- *Road Map for Advanced Power System Planning in Indian States with High Renewable Energy* (NREL 2021)
- *Opportunities for Renewable Energy, Storage, Vehicle Electrification, and Demand Response in Rajasthan's Power Sector* (Chernyakhovskiy et al. forthcoming)

This collection of work helps identify the investment and operational strategies needed to achieve India's clean energy goals and equips key institutions and decisionmakers with the tools, data, and resources to inform and implement these strategies.

Acknowledgments

The authors are greatly indebted to the members of the modeling working group from Karnataka Power Transmission Corporation and Southern Regional Load Dispatch Centre who contributed to inform the model design, input assumptions, and key scenarios. And thank you to Brian Sergi, Patrick Brown, David Palchak, and Jaquelin Cochran (NREL) for their reviews, as well as Isabel McCan, Nicole Leon, and Mike Meshek (NREL) for editorial support. Any errors and omissions are solely the responsibility of the authors.

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List of Acronyms

AC	alternating current
BA	balancing authority
BESS	battery energy storage systems
CC	combined cycle
CT	combustion turbine
DC	direct current
DPV	distributed photovoltaics
FY	fiscal year
GAMS	General Algebraic Modeling System
GJ	gigajoules
GW	gigawatt
GWh	gigawatt-hour
INR	Indian rupee
KA	Karnataka
km	kilometer
kWh	kilowatt-hour
LNG	liquefied natural gas
MW	megawatt
NREL	National Renewable Energy Laboratory
PSH	pumped storage hydropower
PV	photovoltaic
ReEDS	Regional Energy Deployment System
UPV	utility-scale photovoltaics
VOM	variable operation and maintenance
VRE	variable renewable energy

Executive Summary

Karnataka ranks fourth among Indian states in installed capacity of renewable energy, which accounts for over 50% of its resource mix. The state is positioned to play a leading role in India's energy transition and contribute to meeting national targets for renewable energy thanks, in part, to ambitious state goals to develop Karnataka's abundant zero carbon energy resources and plans to phase out new investments in thermal plants.

Power system stakeholders in Karnataka are faced with the challenge of planning a generation portfolio that accounts for the variability of wind and solar resources, meets increasing and shifting electricity demand, and satisfies operational and reliability requirements.

The objective of this study is to evaluate least-cost pathways for Karnataka's electric power system through 2050. The capacity expansion model developed for this study identifies power system investment and operational decisions for every year (2023–2050) for all of India, with detailed representation of the state of Karnataka. The study led to the five high-level results presented below and provides a framework for recurring planning studies to meet changing system conditions and needs.

Karnataka, already a leader in renewable energy, is poised to see even more growth in solar photovoltaics (PV) and wind, in addition to battery energy storage technologies.

In a Reference scenario that includes India's goal of 500 GW of nonfossil capacity by 2030 and Karnataka's state policy to not build new thermal capacity, the modeled least-cost capacity portfolio for Karnataka in 2050 consists primarily of solar PV (52%), wind (23%), and battery storage (21%). In 2050, over 90% of annual generation is from solar PV and wind, with 5% curtailment (Figure ES-1). As the share of renewable energy increases, Karnataka becomes an increasing net exporter of zero carbon energy to the region. The share of Karnataka's annual electricity demand met by generation from outside the state decreases from 11% in 2030 to 5% in 2050, and the share of annual generation transmitted from Karnataka to neighboring states increases from 2% to 9% in the same time frame.

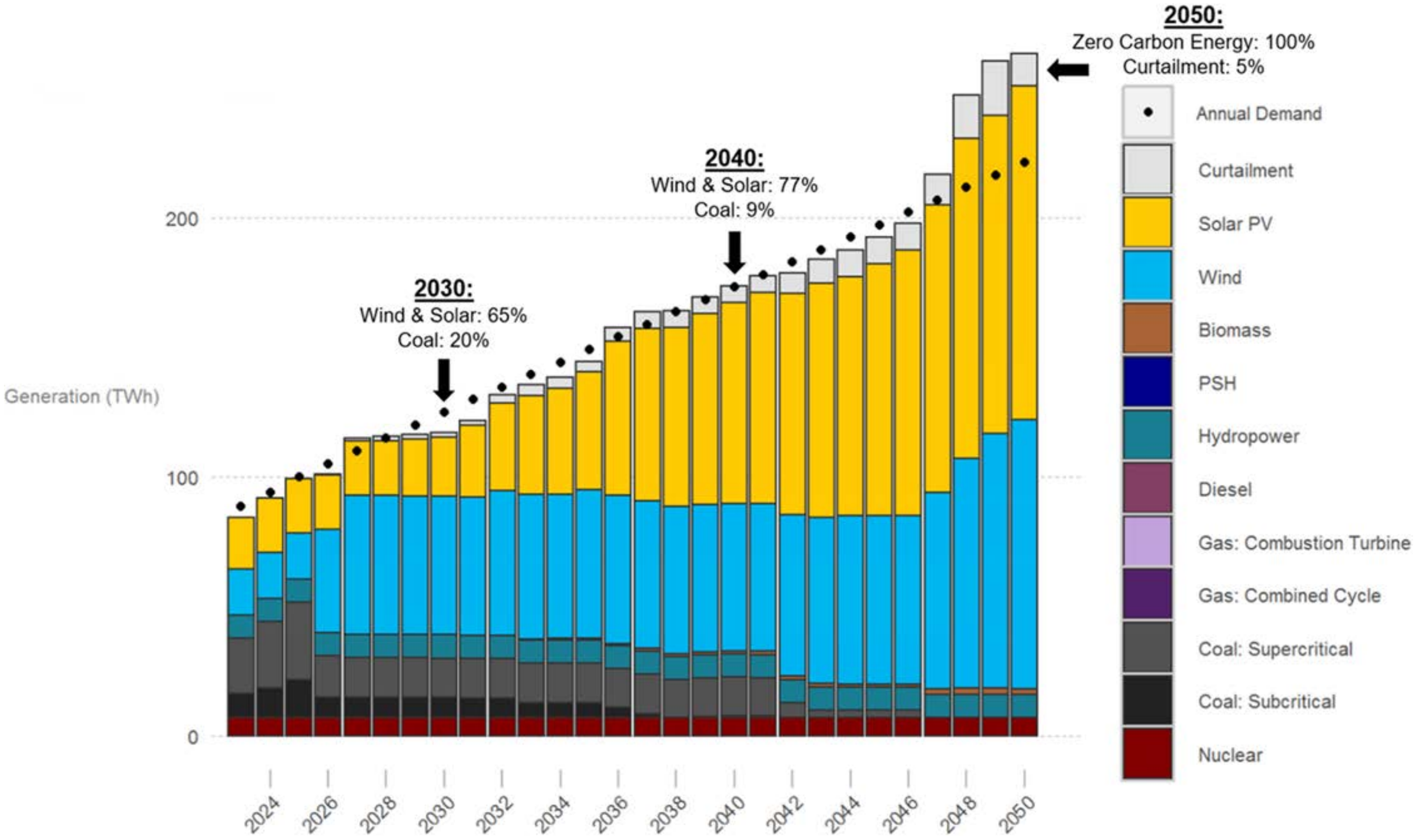

Figure ES-1. Reference scenario: Electricity generation and curtailment in Karnataka

Note: PSH is pumped storage hydropower. Battery Energy Storage Systems (BESS) are not included in the figure because these technologies do not generate new electricity.

National and state-level policies, along with anticipated technology cost trends, can enable a 100% zero carbon energy power system in Karnataka by mid-century.

India's national target to achieve 500 GW of nonfossil capacity by 2030 and Karnataka's state goal to halt investments in new thermal capacity aim to accelerate the transition to a zero carbon electricity supply. In modeled scenarios without India's 500 GW target, subcritical coal retirements in Karnataka are delayed. Furthermore, without Karnataka's existing plan to halt investments in new thermal capacity, investments in natural gas combustion turbine plants would displace some investments in wind, solar PV, and battery storage to meet peak demand (Figure ES-2). Though this outcome assumes sufficient natural gas supply infrastructure, the results of this study show that the current suite of policies is an important driver of the state's zero carbon energy power system transformation.

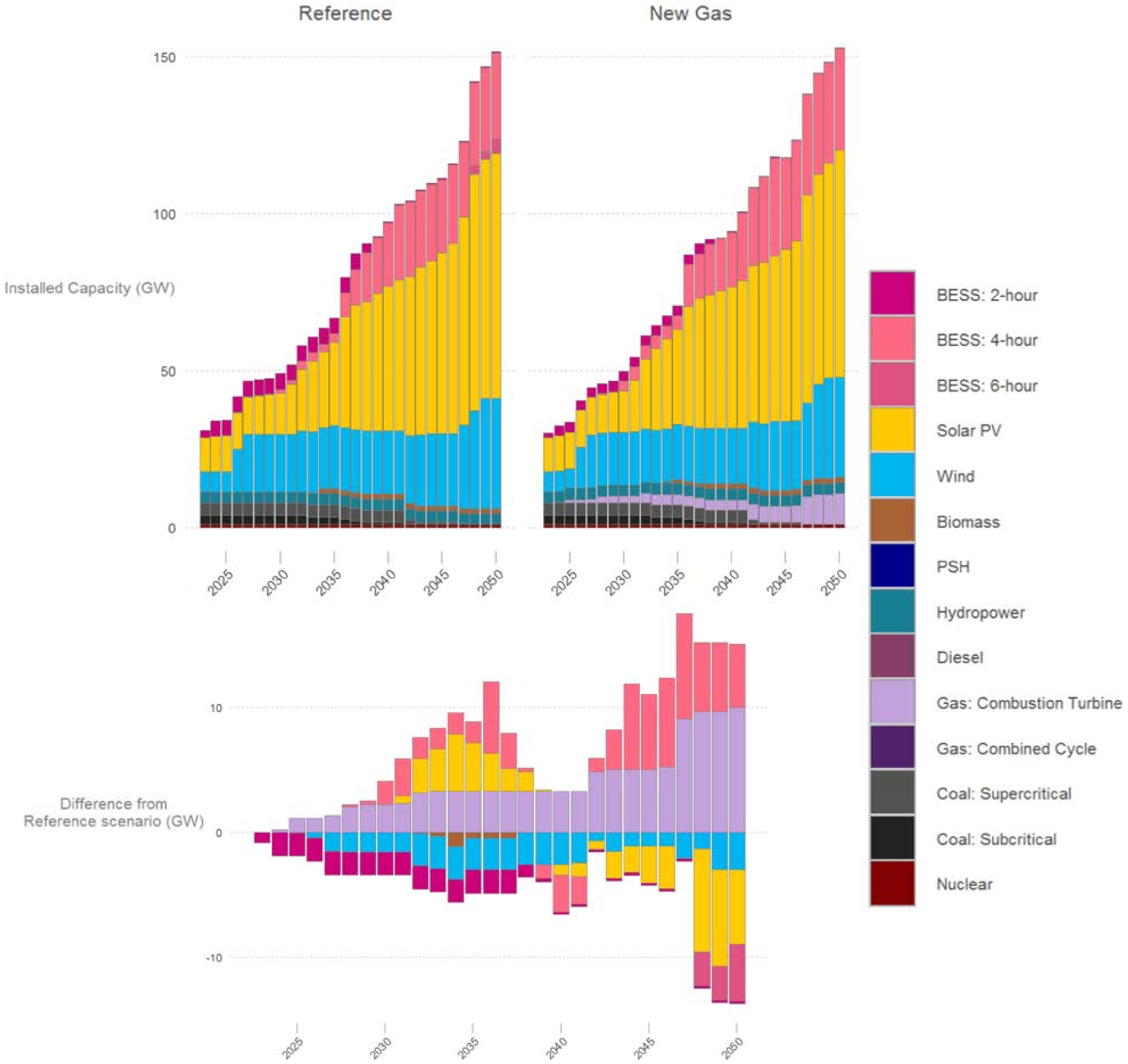

Figure ES-2. Installed capacity of generation technologies in Reference and New Gas scenarios

Note: BESS are battery energy storage systems. PSH is pumped storage hydropower.

Investments in pumped storage hydropower are cost-effective for sites that can achieve greater than 20% capital cost reductions from current investment costs and trends.

Karnataka has resources to develop pumped storage hydropower (PSH) to meet the state's need for energy and flexibility. However, falling costs for other technologies including solar PV, wind, and battery storage might challenge the cost-competitiveness of PSH. Results from scenarios that test investment outcomes under different PSH cost assumptions find that investments in PSH are competitive if PSH capital costs fall by more than 20% ("PSH20" scenario) from current trends (Figure ES-3). Recent proposals for projects in Karnataka indicate these cost reductions are possible for some sites with low civic works requirements. For further PSH development in Karnataka, this result suggests policy support to reduce costs through incentives or technology innovation may be required for PSH to be cost-competitive with other generation and storage technologies. This study did not include site-specific costs in the model. This study also did not investigate scenarios with increased costs for battery technologies; this could also increase the cost-competitiveness of PSH.

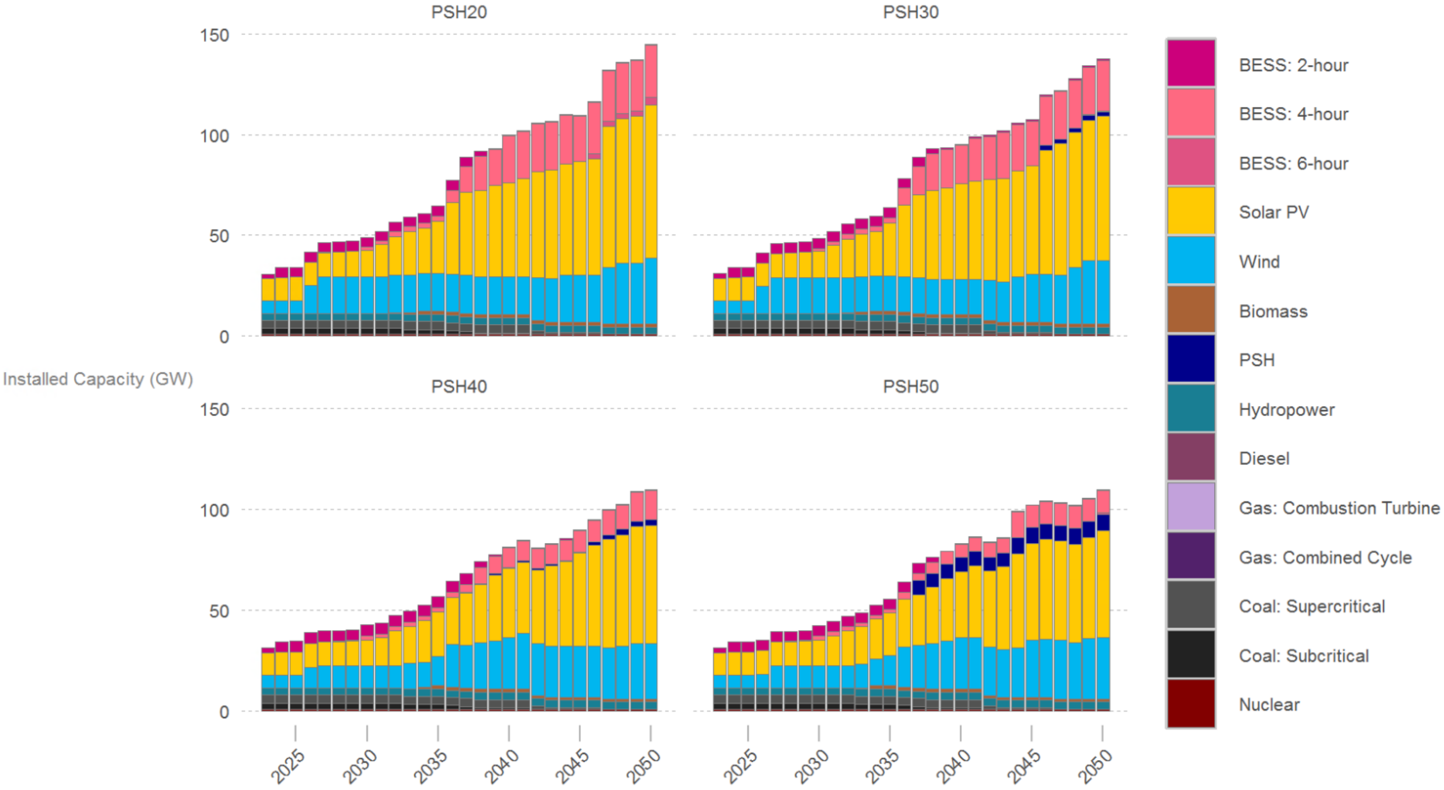

Figure ES-3. Reduced PSH Cost scenarios: Installed capacity of generation technologies in Karnataka

Note: The PSH scenarios refer to assumed reductions in PSH capital costs relative to the Reference scenario (e.g., PSH20 assumes costs are 20% lower, PSH30 assumes costs are 30% lower, etc.).

Flexible loads in the agriculture sector, which account for over a third of Karnataka's annual electricity demand, can further enable renewable energy integration.

Karnataka is already shifting its irrigation pump loads to midday periods to take advantage of abundant and relatively inexpensive solar PV generation. This practice, if continued, can enable up to 2% system-wide cost savings through reduced investment and operating costs. While agriculture load shifting is valuable for all levels analyzed compared to the cost of new generation, the savings are most valuable for the first 5% of agriculture load shifted from peak demand periods to midday; further agriculture load shifting results in a lower savings per unit of energy shifted.

Anticipating increases in electricity demand due to cooling needs can allow for more proactive capacity expansion planning.

Increases in cooling demand in the form of higher air conditioning electricity loads in commercial or residential buildings can have implications for power sector planners and operators. For instance, the modeled results show that increases in residential or commercial cooling demand result in lower installed capacity in Karnataka and more demand being met by generators in neighboring states in a least-cost generation mix. Total demand met by in-state generators decreases from 95% in the Reference scenario to 92% in scenarios with increased cooling demand. This shift happens because the modeled increase in cooling demand only occurs in Karnataka, and only occurs during certain seasons and time-slices. Therefore, it is more cost-effective for in-state demand to be met by out-of-state generators with excess capacity as opposed to building new generation to serve the increased demand for only specific portions of the year. However, if Karnataka is experiencing higher cooling demand, there will likely be correlated changes in demand in neighboring states. Thus, increased coordination between state planners and operators may be required to meet changes in future demand.

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1 Introduction

As of April 2022, the southern state of Karnataka had 15.9 GW of installed renewable energy capacity,[1] ranking it fourth among Indian states (MNRE 2022). Renewable energy accounts for the majority of installed capacity, at 53.1%, with 31.6% for coal, 12.3% for large hydropower, 2.9% for nuclear, and 0.1% for diesel (CEA 2022). The recently approved *Karnataka Renewable Energy Policy 2022-2027* aims to spur additional investments in renewable energy development and manufacturing, as well as contribute to the national target of 500 GW of nonfossil power capacity by 2030. The state policy aims to achieve an additional 10 GW of renewable energy capacity, including 1 GW of rooftop solar photovoltaics (PV), by 2027 (Government of Karnataka Energy Department 2022).

Meeting the 2027 state-level target, 2030 national target, and longer-term objectives for low-carbon development will require robust planning to ensure a cost-effective and reliable power system capable of serving increased demand from conventional electricity consumers and enabling the electrification of other sectors such as transportation. Most of Karnataka's current, and likely future, renewable energy capacity consists of wind and solar PV, both of which are subject to variable weather. Therefore, planners need to ensure generation resources will be available to balance supply and demand across daily, seasonal, and yearly timescales. Planning transmission alongside generation can enable export of excess renewable energy to demand centers and should consider the role of energy storage, which can provide transmission congestion management, operating reserves, resource adequacy, and system flexibility.

To support the government of Karnataka in this transition and inform state policymakers, regulators, planners, and grid operators on system needs through 2050, the National Renewable Energy Laboratory (NREL) undertook a long-term capacity expansion planning study. The remainder of this report is organized as follows: Section 2 describes the model used to conduct this study and the scenarios assessed, Section 3 covers the results from the Reference (business-as-usual) scenario, Sections 4 and 5 discuss results from alternative supply-side and demand-side scenarios, and Section 6 summarizes the key findings and implications for power sector stakeholders.

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[1] According to India Ministry of New and Renewable Energy (MNRE) statistics, renewable power capacity includes small hydropower, wind, solar, and various forms of biopower (e.g., waste-to-energy and bagasse cogeneration).

2 Modeling Approach and Assumptions

The primary tool used in this study is NREL's Regional Energy Deployment System India (ReEDS-India) capacity expansion model, which identifies the least-cost mix of generation, transmission, and storage technologies required to meet future system needs through 2050. Scenario analysis is used to address uncertainties in future technology costs, fuel availability, electricity demand, and policies.

2.1 Modeling Framework

Capacity expansion models must balance the need for detailed representation of the electricity sector with computational complexity. Planning tools vary significantly in their treatment of operating constraints, energy prices, and demand projections, as well as temporal and geographic resolution. For systems such as Karnataka's, where variable renewable energy (VRE) technologies (e.g., wind and solar PV) might play an increasing role in the future generation mix, the appropriate tool should capture the diversity of candidate VRE technologies and their applications, the location-dependent quality of these resources, and the inherent uncertainty and variability of wind and solar generation.

The ReEDS-India capacity expansion model is used for this study due to its rich assessment of the technical, geographic, and operational aspects of VRE deployment. This model takes load forecasts, generation and transmission infrastructure costs, fuel costs, and details of the existing and planned power system as inputs and employs linear optimization to minimize the net present value of generation and transmission investments and operating costs. Other major constraints include balancing of electricity supply and demand, resource supply limits, planning and operating reserve requirements, transmission limitations, and policy targets. These constraints are met by considering a broad portfolio of generation, storage, and transmission technologies. The outputs of ReEDS-India include generator capacity additions, generator retirements, additional transmission capacity on different corridors, transmission power flows, and reserve requirements for each year from 2020 to 2050. A range of potential future scenarios is assessed, providing insights for planning agencies, utilities, and local stakeholders about trends and sources of uncertainty.

More information about ReEDS can be found in Ho et al. (2021), and details on its application to India can be found in Rose et al. (2020). The model is implemented in the General Algebraic Modeling System (GAMS) programming language. A publicly available version of the ReEDS model developed for national-level planning in India can be accessed from NREL's "Regional Energy Deployment System Model" web page at https://www.nrel.gov/analysis/reeds/.

2.2 Model Design and Assumptions

The following section provides details on the input assumptions in the ReEDS-India model for the state of Karnataka regarding spatial resolution, electricity demand, supply, transmission, and reliability. For details on inputs included in the model for the rest of India, see Chernyakhovskiy et al. (2021).

2.2.1 Model Regions

The model includes three levels of spatial resolution: regions, balancing areas (BAs), and resource regions. Regions are the five operating regions of India, namely the Northern, Northeastern, Eastern, Southern, and Western regions. Each region is composed of BAs representing states and union territories that are connected by the transmission network (Figure 1). Electricity demand, transmission lines, and non-VRE generators are aggregated for each BA. For this study, the state of Karnataka was further divided into six BAs that represent the six control regions of the state to include a finer spatial resolution (Figure 2). Within each BA, there are multiple resource regions designed to capture differences in wind and solar resources at a higher level of granularity. Thirty resource regions are included in Karnataka, one for each state district.

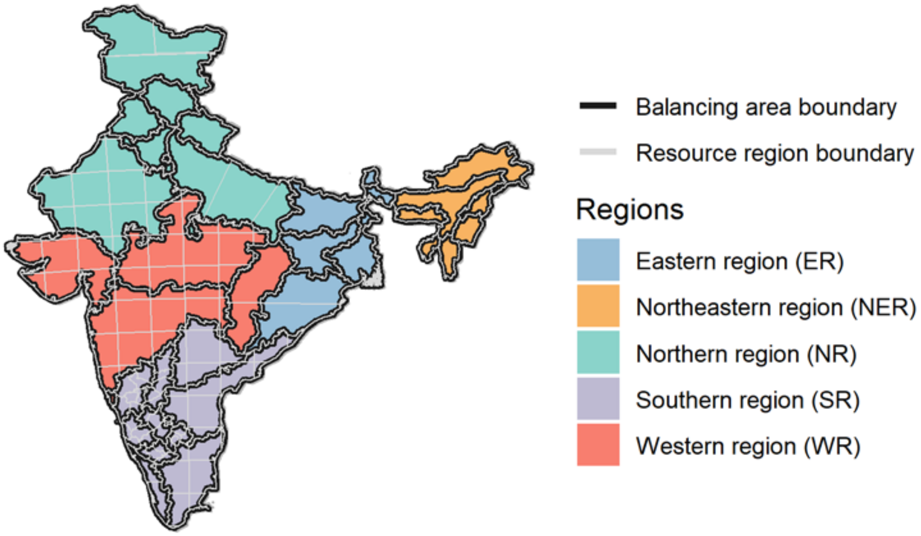

Figure 1. Regions, balancing areas (BAs), and resource regions in India

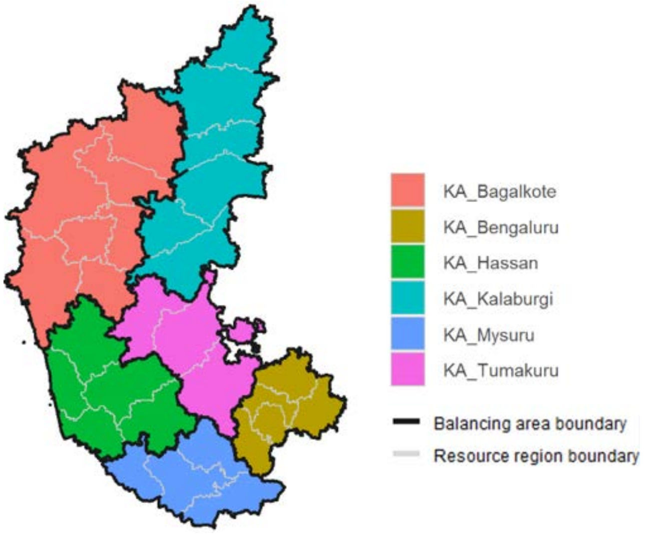

Figure 2. BAs and resource regions in Karnataka

Note: KA is Karnataka.

2.2.2 Electricity Demand

Annual electricity demand is represented with 35 time-slices, or representative hours, designed to capture changes in seasonal and daily demand patterns, as well as wind and solar resource availability. The time-slices include five seasons with seven representative times of day per season. For more information on the design of the time-slices, see Rose et al. (2020). The electricity demand forecast is based on the 19th Electric Power Survey published by the Central Electricity Authority (CEA 2018a). The approach used to forecast peak demand and total electricity consumption through 2050 for each BA is described by Chernyakhovskiy et al. (2021). Table 1 summarizes the assumed growth in peak demand and annual energy consumption for each Karnataka BA.

Table 1. Assumed Growth in Karnataka Electricity Demand, 2022–2050

Karnataka BA	Annual Energy Consumption (TWh)		Peak Demand in Time-Slice (GW)	
	2022	2050	2022	2050
Bagalkote	17.6	47.0	3.3	8.8
Bengaluru	19.1	50.8	3.2	8.5
Hassan	6.8	18.2	2.8	7.5
Kalaburgi	10.2	27.1	3.3	8.8
Mysuru	10.2	27.1	2.7	7.1
Tumakuru	19.2	51.1	3.2	8.5

2.2.3 Electricity Supply

The generation fleet is represented by several different technology types, each with its own techno-economic parameters. Table 2 summarizes the generation technologies considered in the model.

Table 2. Generation Technology Candidates

Thermal Technologies	Renewable Technologies	Storage-Based Technologies
Biomass: Cogeneration Bagasse Coal: Subcritical Coal: Supercritical Diesel Gas: Combined Cycle (CC) Gas: Combustion Turbine (CT) Lignite: Subcritical Nuclear Waste Heat Recovery	Distributed PV (DPV) Hydropower: Pondage Hydropower: Run-of-River Hydropower: Storage (reservoir) Utility-Scale PV (UPV) Wind: Land-Based	Battery Energy Storage Systems (BESS): 2-hour BESS: 4-hour BESS: 6-hour BESS: 8-hour BESS: 10-hour Pumped Storage Hydropower (PSH): 12-hour

All units of the same technology within a BA are aggregated, with the exception of wind and solar, which are aggregated by resource region. To capture differences in cost and performance of units of the same technology within a BA or resource region, we cluster units into "performance bins" based on their generation cost and operating efficiency. Information on this clustering approach is presented in Rose et al. (2020).

Input data for exogenously defined capacity include existing capacity, planned capacity additions, and planned retirements sourced from Palchak et al. (2017), CEA (2018b), and consultations with staff from the Southern Regional Load Dispatch Centre and Karnataka Power Transmission Corporation Limited. The model represents only the physical location of generators; plant ownership (e.g., state, federal, and private) is not considered for investments within Karnataka.

Table 3 summarizes the installed capacity assumed to exist at the end of 2022.

Table 3. Summary of Installed Capacity (MW) by Technology and Karnataka BA at End of 2022

Technology	Bagalkote	Bengaluru	Hassan	Kalaburgi	Mysuru	Tumakuru	Total
Coal: Subcritical	0	0	1,200	4,280	0	0	5,480
Coal: Supercritical	3,200	0	0	1,600	0	0	4,800
Diesel	0	128	0	0	0	0	128
DPV	173	303	151	0	0	136	763
Hydropower: Pondage	132	0	233	28	59	0	452
Hydropower: Storage (reservoir)	1,610	0	1,490	0	0	0	3,100
Nuclear	880	0	0	0	0	0	880
UPV	1,088	337	0	1,917	352	3,341	7,034
Wind: Land-Based	2,941	0	0	918	1	1,083	4,942
Total	**10,023**	**767**	**3,074**	**8,743**	**411**	**4,560**	**27,579**

Planned capacity additions include committed projects with known locations and commissioning dates. Exogenously defined capacity retirements include planned retirements and age-based retirements based on the plant's economic lifetime and commissioning date. Investments in distributed PV (DPV) were forecast using the Distributed Generation Market Demand Model with local data on electricity prices, rooftop characteristics, solar irradiance, and consumer characteristics. In total, over 25 GW of DPV is forecast to be adopted by 2050 with the residential sector accounting for the largest share of final DPV capacity, followed by the commercial and industrial sectors (Das et al., 2022).

Future electricity supply needs can be met by any of the thermal, renewable, or storage-based technologies presented in Table 2. The optimal mix of technologies is based on several factors, including the cost of development, operation and maintenance costs, policy targets, and resource availability. Appendix A.1 contains the assumptions about technology costs, performance, and investment constraints used in the model.

2.2.4 Transmission

ReEDS-India uses an aggregated transmission network, capturing the combined carrying capacity of interstate lines between BAs based on Palchak et al. (2017), which represents a close approximation of existing transfer capacities with reliability-based flow limits. A transportation, or pipe flow model, approximates power flows between BAs.[2] Table 4 shows the available transfer capacities between Karnataka BAs and nearby states based on existing lines in 2022.

Table 4. Available Transfer Capacity Between Karnataka BAs and Nearby States in 2022

Karnataka BA	Nearby State	Line Type	Transfer Capacity (MW)
Bagalkote	Maharashtra	AC	6,012
Bengaluru	Odisha	DC	2,500
	Tamil Nadu	AC	4,563
Kalaburgi	Telangana	AC	917
Mysuru	Kerala	AC	1,165

Transmission expansion is modeled as additional transfer capacity (MW) between BAs built at a BA-to-BA-specific per unit cost (INR/MW-km). Using this approach, the total cost of adding transfer capacity between two BAs depends on the capacity being added and the distance between the BAs. Appendix A.3 contains the transmission capital cost assumptions for each Karnataka BA.

2.2.5 Reliability

We include two types of reliability constraints: a planning reserve margin and an operating reserve requirement. The planning reserve margin requires that each of India's five operating regions (e.g., Southern Region) maintain adequate installed capacity to meet peak demand plus 15% in every season (CEA 2019). The amount of installed capacity considered "firm," or available to contribute to the planning reserve margin requirement, depends on the technology type. Conventional generation technologies receive full capacity credit toward meeting the planning reserve margin with no seasonal variation. The firm capacity for dispatchable hydropower technologies (i.e., hydropower pondage and storage) is based on the installed capacity times the average seasonal capacity factor for that technology. For wind, solar, and storage technologies, firm capacity is estimated based on hourly simulations of generation and demand to determine each technology's contribution to reduce the coincident peak net load in each region and season. The operating reserve requirement is equal to 5% of national demand in each time-slice. The contribution of different technologies to the operating reserve requirement is limited by the ramping capability for that technology. The assumptions for operating reserve costs and technology-specific contributions (Appendix A.4) are based on Ho et al. (2021).

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[2] A transportation model ignores reactive power and Kirchhoff's current and voltage laws. We assume that power flows from one region to another without impacting the rest of the network.

2.3 Study Scenarios

The study considers the six scenarios outlined in Table 5. The Reference scenario represents a business-as-usual case, in which trends in electricity demand follow existing forecasts, technology costs follow anticipated changes in NREL's Annual Technology Baseline "Mid-Case" projections, and national and state policies for power sector investments remain constant. Details about these default assumptions are presented in Section 2.2. The 2030 RE Policy refers to India's national-level goal to achieve 500 GW of nonfossil power capacity and generate 50% of its electricity from renewable energy by 2030. These targets were incorporated into the model as national-level constraints that have implications at the state level. Another default assumption is that no new coal or gas power plants will be built in Karnataka, as the state government has announced it will stop investing in new thermal power plants (Business Standard 2021). All scenarios allow upgrades from hydropower storage plants to pumped storage hydropower (PSH) plants in Karnataka.

Table 5. Description of Scenarios Analyzed for Karnataka

Scenario Name	2030 RE Policy	New Gas Capacity in Karnataka	New Coal Capacity in Karnataka	Technology Costs	Electricity Demand
Reference	Yes	No	No	Default	Default
No RE Policy	No	No	Yes	Default	Default
New Gas	Yes	Yes	No	Default	Default
Reduced PSH Cost	Yes	No	No	Cost reductions in PSH and upgrades to PSH	Default
Agriculture Load Shifting	Yes	No	No	Default	Agriculture demand shifted from peak period to afternoon period
Increased Cooling Loads	Yes	No	No	Default	Increased demand in morning and afternoon periods (commercial) or peak and sunset periods (residential)

The rest of the scenarios can be divided into supply-side scenarios (No RE Policy, New Gas, Reduced PSH Cost) and demand-side scenarios (Agriculture Load Shifting, Increased Cooling Loads). The supply-side scenarios investigate the impacts of changes in policy related to generation sources or technology costs, while demand is kept unchanged from the Reference scenario. The results show how changes to certain supply side conditions influence the least-cost generation portfolio. The demand-side scenarios investigate the impacts of changes in demand due to various factors (e.g., policies, consumer behavior, and appliance costs) while keeping the generation parameters fixed. Therefore, the results show how the least-cost generation portfolio is sensitive to changes in electricity consumption.

3 Reference Scenario Results

The results from the Reference scenario indicate Karnataka is poised to see significant growth in VRE capacity and battery energy storage systems (BESS) in the coming decades. Figure 3 displays the evolution in installed capacity of electricity supply through 2050 in Karnataka. In 2050, the state's capacity mix consists of 100% zero carbon resources: solar PV (51.5%), wind (23.1%), BESS: 4-hour (18.1%), BESS: 6-hour (3.0%), hydropower (2.3%), biomass (1.0%), nuclear (0.6%), and BESS: 2-hour (0.3%). Each year, an average of 4.2 GW of new capacity is added. This marks an increase in capacity deployment compared to the average of 2.6 GW of new capacity added per year over the 2016-2021 period. Further, BESS investments shift to longer duration systems over the study period, from 2-hour BESS (primarily 2023–2038) to 4-hour BESS (primarily 2032–2050) to 6-hour BESS (primarily 2048–2050).

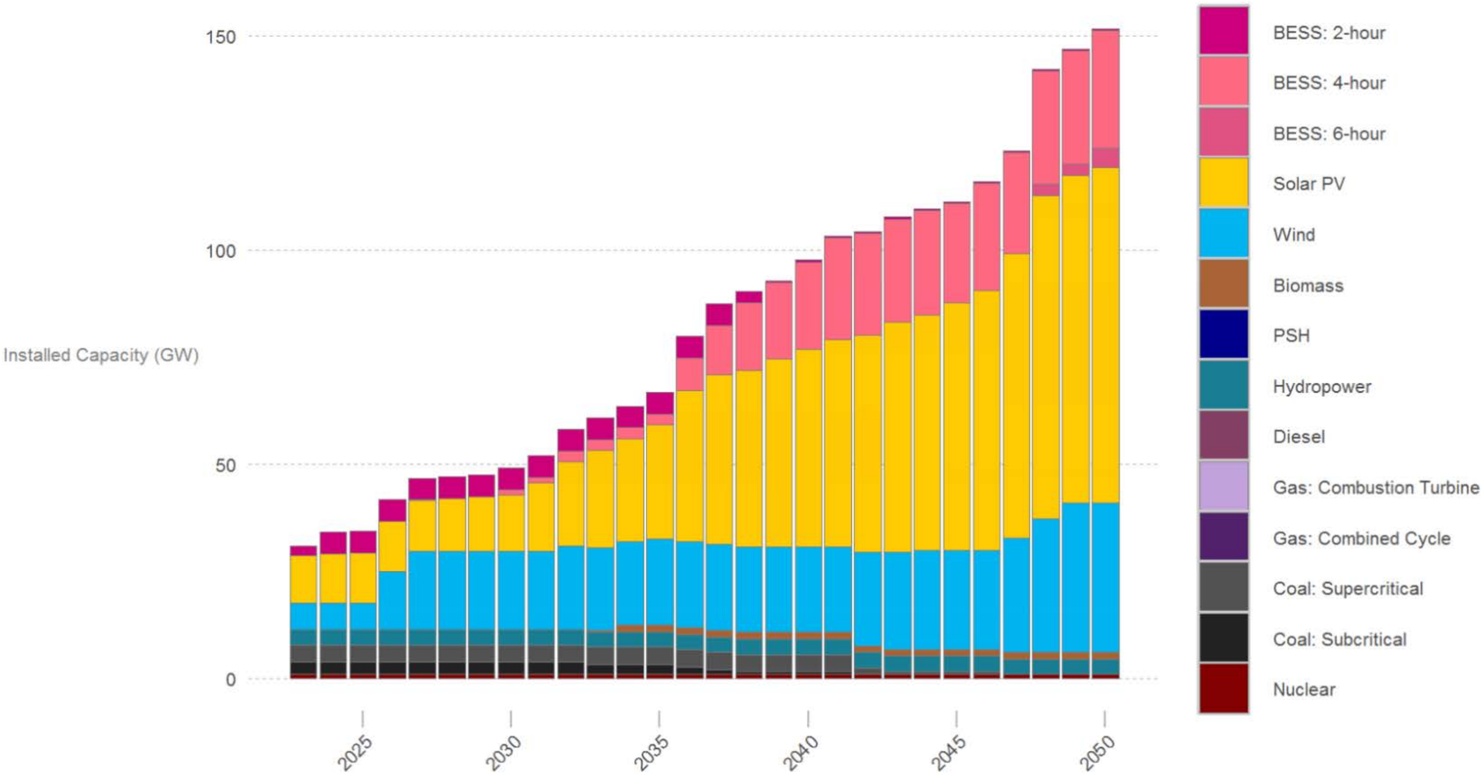

Figure 3. Reference scenario: Installed capacity of generation technologies in Karnataka

Note: BESS are battery energy storage systems. PSH is pumped storage hydropower.

New wind development is predominantly in the Kalaburgi and Tumakuru regions; utility-scale solar PV investments are more widespread across the Bagalkote, Hassan, and Tumakuru regions; and DPV development is predominantly in the Bengaluru region (Figure 4).

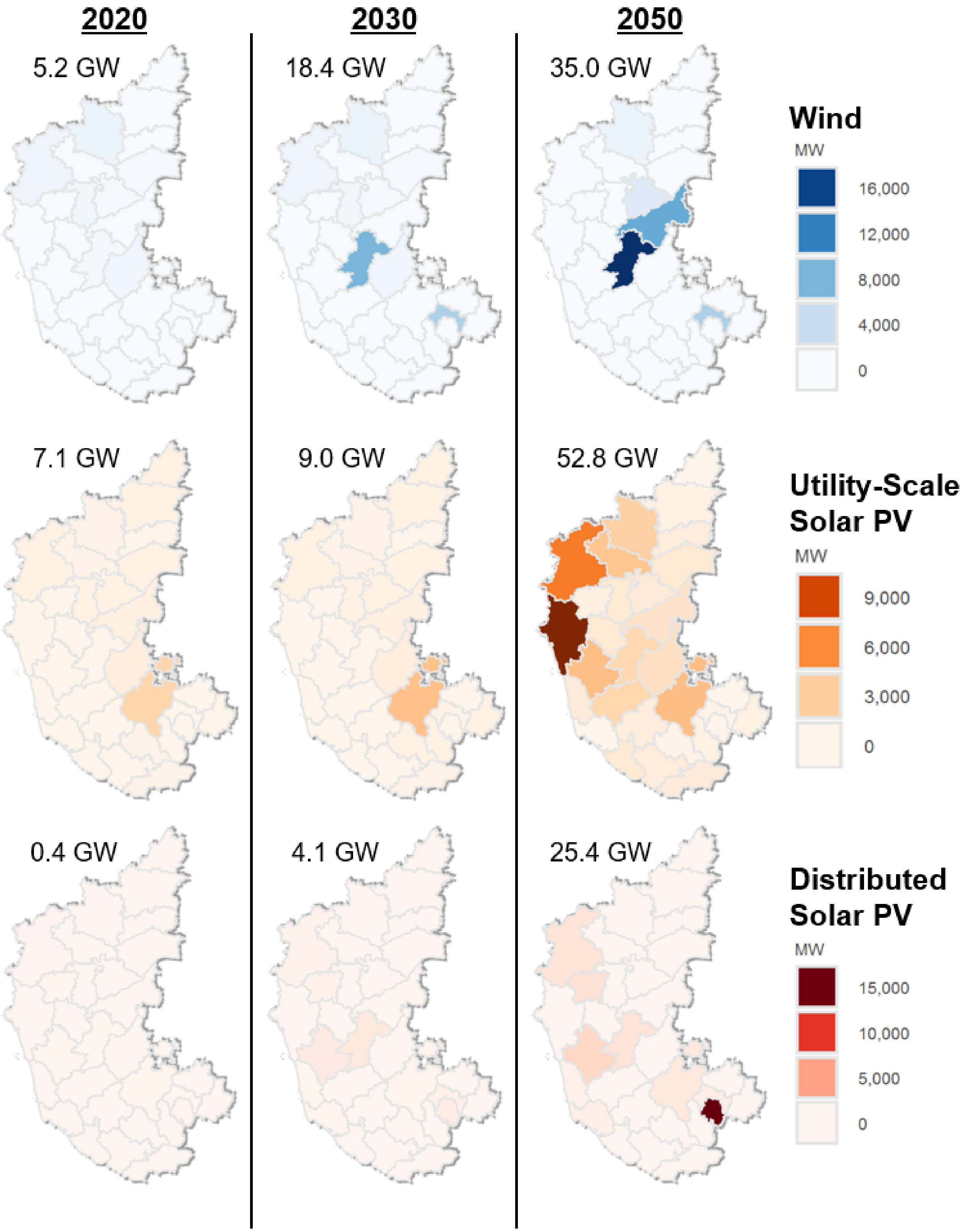

Figure 4. Reference scenario: Geographic distribution of VRE capacity in Karnataka

By 2050, zero carbon energy sources account for 100% of electricity generation in the state (Figure 4). Wind and solar PV account for over 90% of generation, up from 41% in 2020. The generation from BESS is not displayed in the figure because these technologies do not generate new electricity.

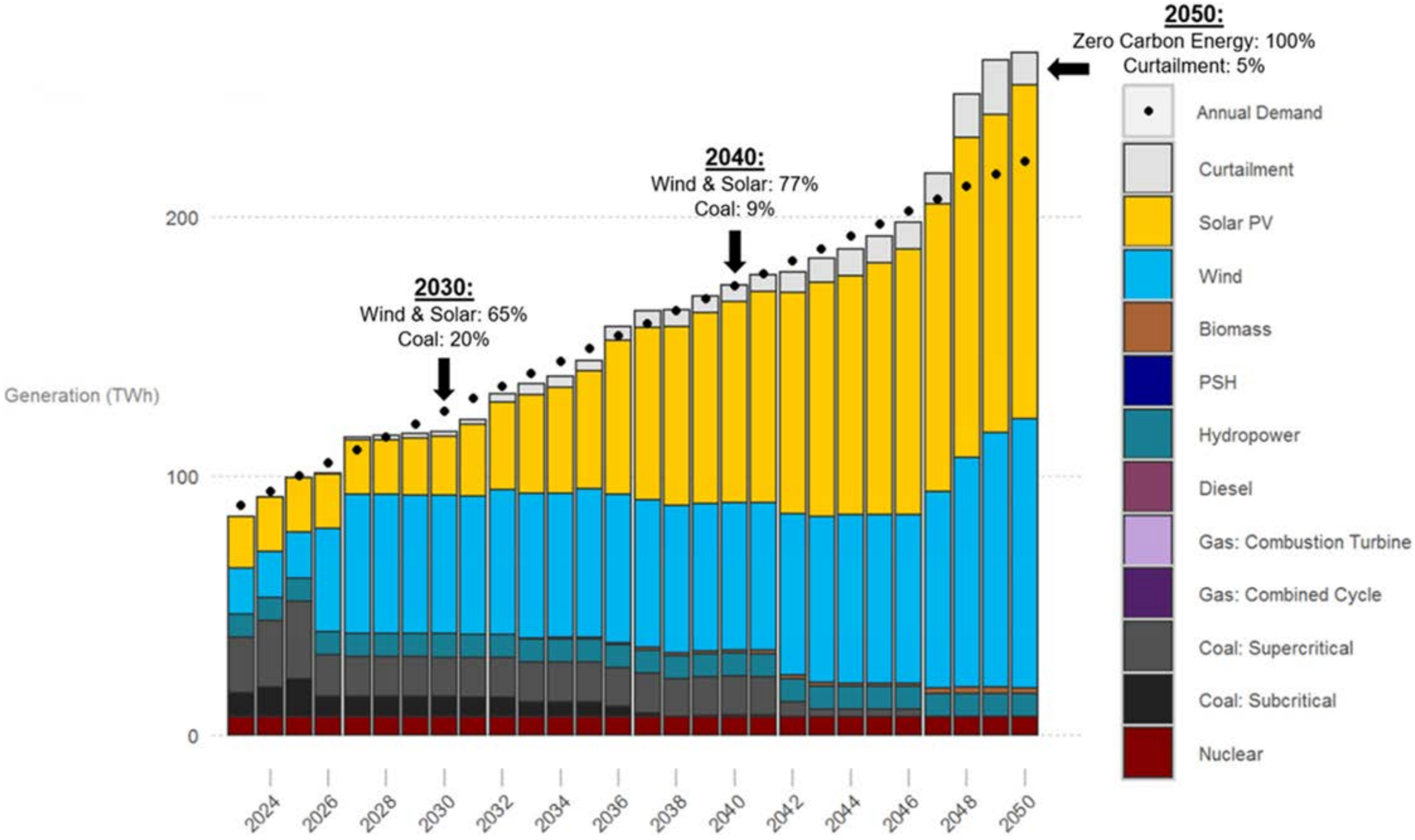

Figure 5. Reference scenario: Electricity generation and curtailment in Karnataka

Note: PSH is pumped storage hydropower. Battery Energy Storage Systems (BESS) are not included in the figure because these technologies do not generate new electricity.

As thermal generation is replaced with wind and solar PV, Karnataka becomes a regional supplier of renewable electricity. Generation from subcritical and supercritical coal plants is phased out by 2038 and 2047, respectively, as plants reach the end of their assumed economic life. From 2030 to 2050, the percentage of Karnataka's annual electricity demand met by out-of-state generation decreases from 11% to 5% while the percentage of Karnataka's annual electricity generation that is transmitted to neighboring states increases from 2% to 9%.

Figure 6 shows the technologies dispatched to meet demand in each time-slice for the 2050 model year. For each representative hour, the black dot indicates the electricity demand (GW) and the bar chart shows the mix of generation resources dispatched to meet demand during that period. Negative values indicate charging for BESS or PSH technologies. Periods when the black dot exceeds the bar indicate Karnataka is importing power from generation resources outside the state.

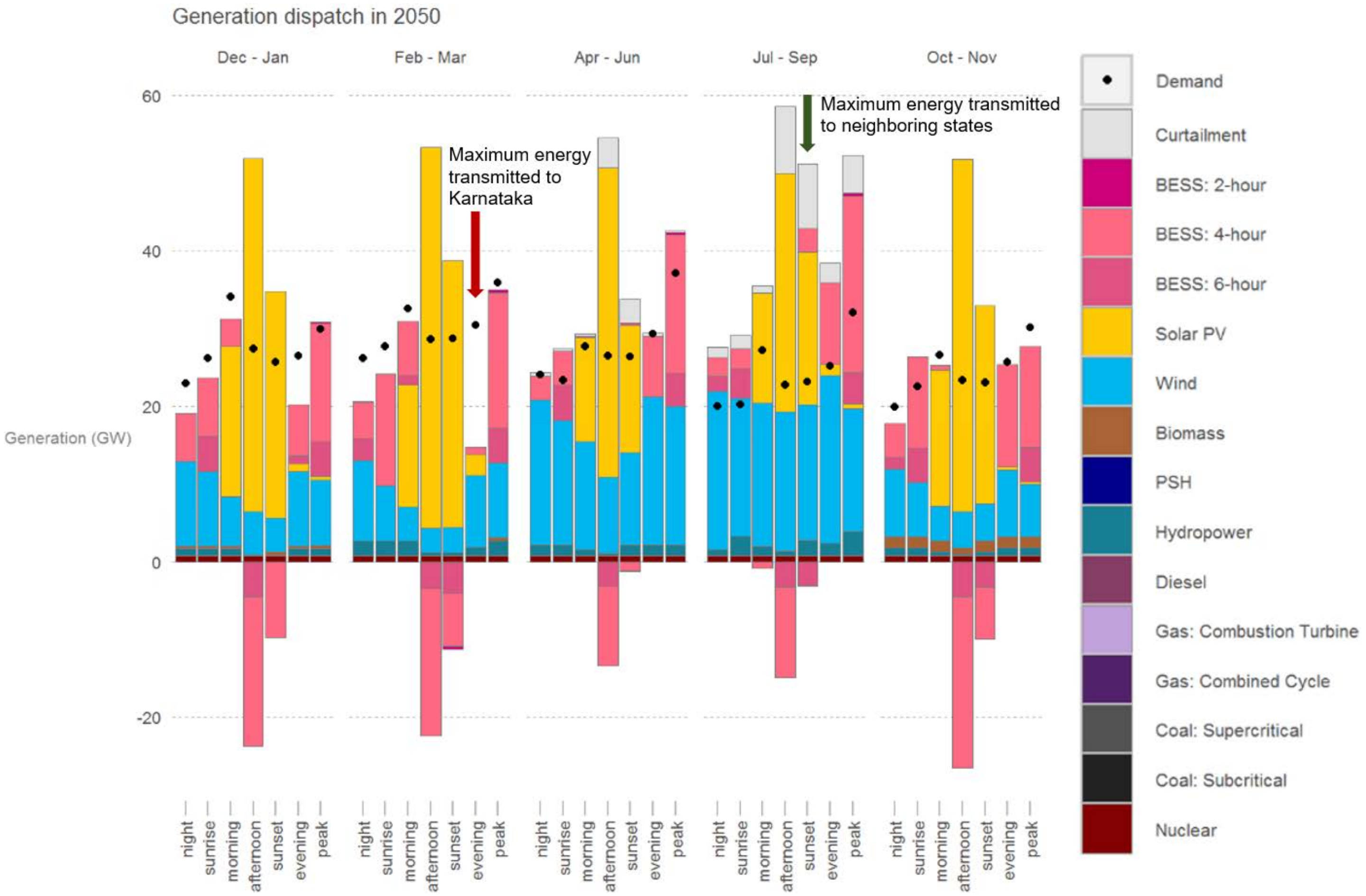

Figure 6. Reference scenario: Generation dispatch and demand in Karnataka for time-slices and seasons in 2050

In 2050, imported electricity from neighboring states is used to balance supply and demand during parts of the day from October–March, with the highest level of imports happening during the evening period in February–March. By contrast, the state is expected to export renewable energy generation to neighboring states in midday throughout the year, when solar generation is highest, and during the high wind months of April–September.

Increased shares of VRE generation require greater flexibility from other grid resources to balance supply and demand. In the low-wind seasons of February–March and October–November, daily wind generation falls by 65% compared to July–September, and increased generation from biomass and imports from neighboring states is thus required. While biomass and imports can respond to seasonal variations in net load, energy storage in the form of PSH and BESS play a larger role in intraday load following. Energy storage helps maximize the use of solar PV generation by storing energy during the day (i.e., the negative bars in Figure 6) and discharging during peak demand or evening periods when solar generation is not available.

Investments in transmission occur between regions of Karnataka and between Karnataka and nearby states. Figure 7 summarizes the total transmission additions over the model period.

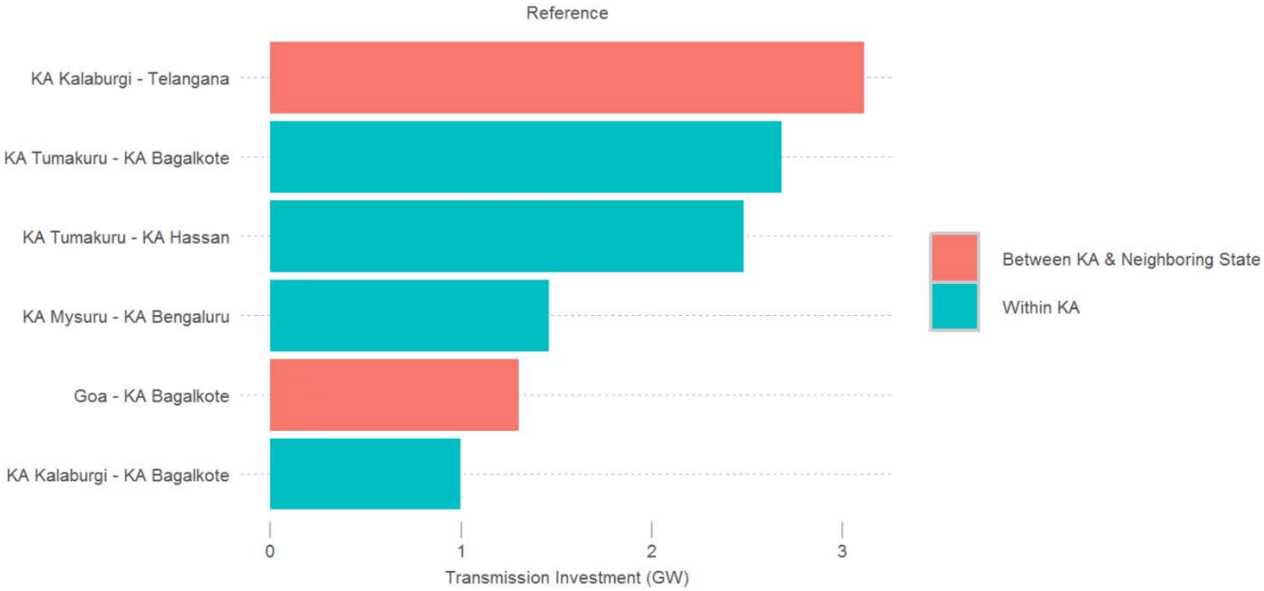

Figure 7. Reference scenario: Cumulative transmission investments through 2050

Investments in transmission enable solar PV and wind generation to be transmitted from Bagalkote and Tumakuru, respectively, to load centers in Bengaluru and nearby states. Over 60% of new transfer capacity connected to Karnataka is added between in-state BAs to enable greater intrastate power flows; the remaining additions include over 3 GW between Kalaburgi and Telangana and over 1 GW between Goa and Bagalkote. The majority, 79%, of transmission investments connected to Karnataka occur at the end of the model period, 2040 – 2050, as existing transmission corridors become insufficient to transfer the increased quantums of power from renewable generation regions to load centers.

4 Supply-Side Scenarios

The supply-side scenarios investigate the impacts of changes in policy and technology costs while keeping demand unchanged from the Reference scenario. The following results show how changes to certain parameters (e.g., bans on fossil-fuel generators or capital costs for PSH) influence generation investments over time.

4.1 No RE Policy

To analyze the impact of policy changes on Karnataka's long-term power sector trajectory, the No RE Policy scenario removes the 2030 RE Policy's national-level constraints and allows investments in new coal in the state. Figure 8 shows the difference in installed capacity in Karnataka for each year in the No RE Policy scenario compared to the Reference scenario.

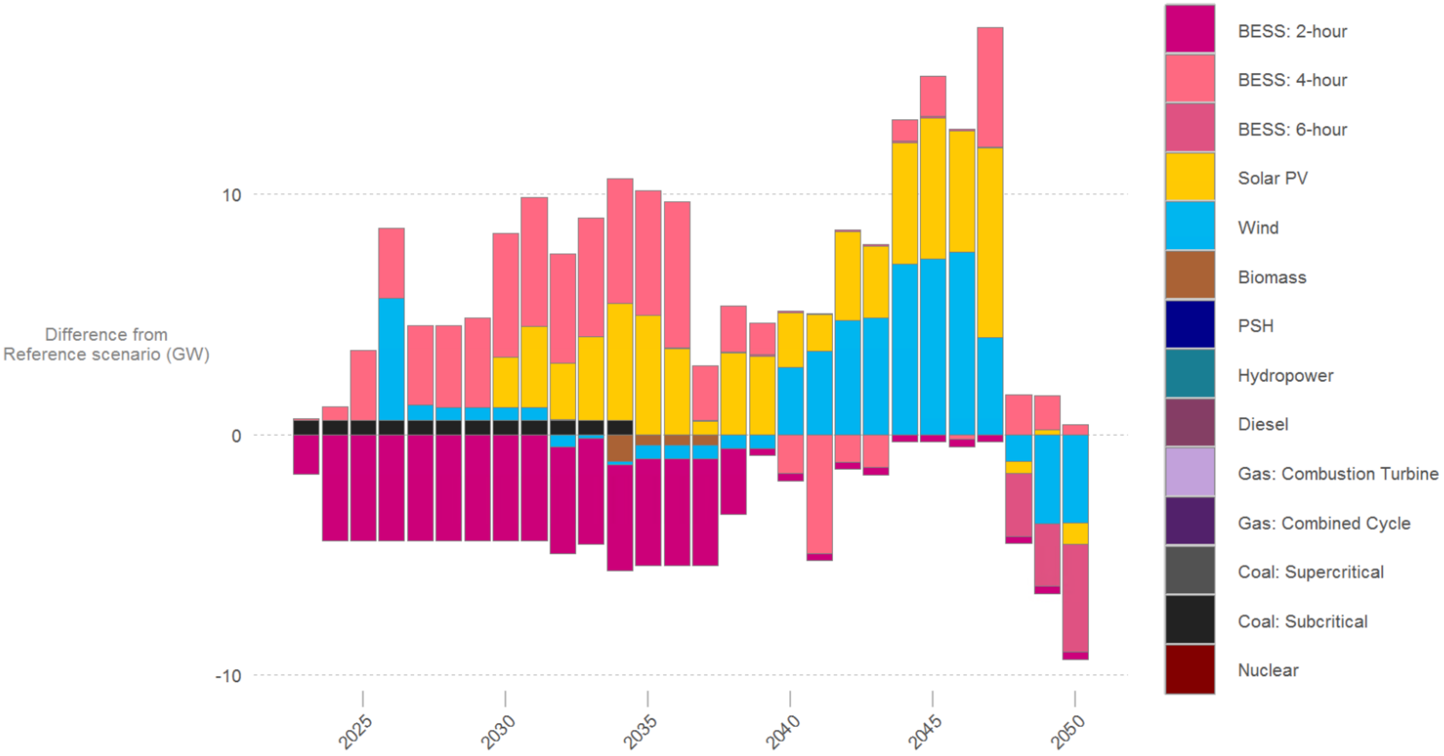

Figure 8. No RE Policy scenario: Difference in installed capacity of generation technologies compared to Reference scenario

In the absence of national and state zero carbon energy policies, retirements of subcritical coal are delayed through 2034, 2-hour BESS are replaced with 4-hour BESS through 2039, and there are no cost-effective investments in 6-hour BESS. The delayed retirement of subcritical coal results in less demand that needs to be met by a combination of renewable energy and storage through 2034 compared to the Reference scenario. In those years, the modeled results suggest that meeting this reduced demand is more cost effective with increased capacities of 4-hour BESS, solar, and wind, as opposed to 2-hour BESS. The reduced capacity of wind and solar after 2047 could also explain why 6-hour BESS is not cost-effective in this scenario, as greater capacities of renewable energy tend to increase the cost-effectiveness of longer-duration storage. Overall, removing the 2030 RE Policy national-level constraints reduces the capacity of wind and solar built in Karnataka by close to 5 GW, or 4%, in 2050 compared to the Reference scenario. However, this decrease does not begin until after 2047, suggesting that overall trends in wind and solar deployment may occur independent of national policies to accelerate their uptake. Policies do influence early retirement of coal capacity in the state and allowing new coal development does not result in new coal capacity being built, indicating coal is not cost-competitive with VRE or storage technologies for new construction.

Although the general trends for the No RE Policy scenario are consistent with those of the Reference scenario, there are slight differences in total generation by 2050 for the former; namely, Karnataka's net electricity imports increase. Compared to the Reference scenario in 2050, annual demand met by imports increases from 5% to 8% and annual generation that is exported decreases from 9% to 6.5%.

4.2 New Gas

The New Gas scenario allows new investments in natural gas plants in Karnataka to investigate the impact that gas development could have on the state's power sector development. This scenario assumes sufficient pipeline or other gas transportation infrastructure is available in Karnataka and allows builds of either combined cycle (CC) or combustion turbine (CT) gas generators. In this scenario, gas CT capacity comes online starting in 2025. By 2050, 10 GW of gas CT and around 5 GW of 4-hour BESS capacity displaces a similar total capacity of wind, solar PV, and 6-hour BESS (Figure 9).

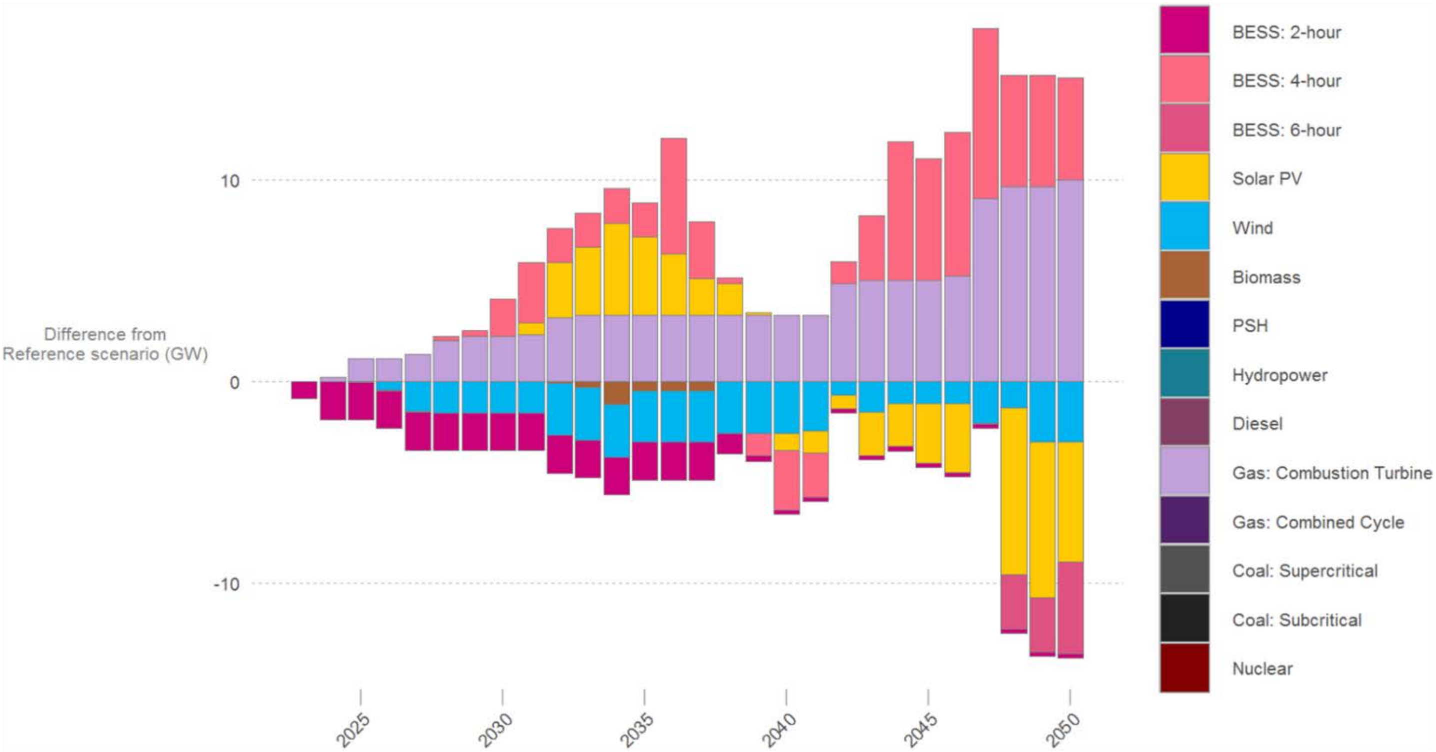

Figure 9. New Gas scenario: Difference in installed capacity of generation technologies compared to Reference scenario

Thus, assuming sufficient fuel is available, gas CT capacity could be economically developed. Compared to combined cycle (CC) gas units, CTs have a lower capital cost but higher operating cost, making them cost-effective for providing firm capacity or generation during limited periods of the year. Over the modeled period, the capacity factor for the gas CT fleet in Karnataka does not exceed 5%. By 2050, gas CT capacity is used to meet demand during peak load periods of December–January and April–June, as well as throughout the day in October–November, when wind generation is the lowest (Figure 10). As a percentage of India's annual gas consumption for electricity generation, the fuel used in Karnataka increases from 4% in 2030 to 16.5% in 2050. This increase can also be attributed to the fact that outside of Karnataka, the capacity of gas CT in India decreases by approximately 5.4 GW in 2050. The additional generation from in-state gas CT capacity displaces imports from nearby states in October–November compared to the Reference scenario.

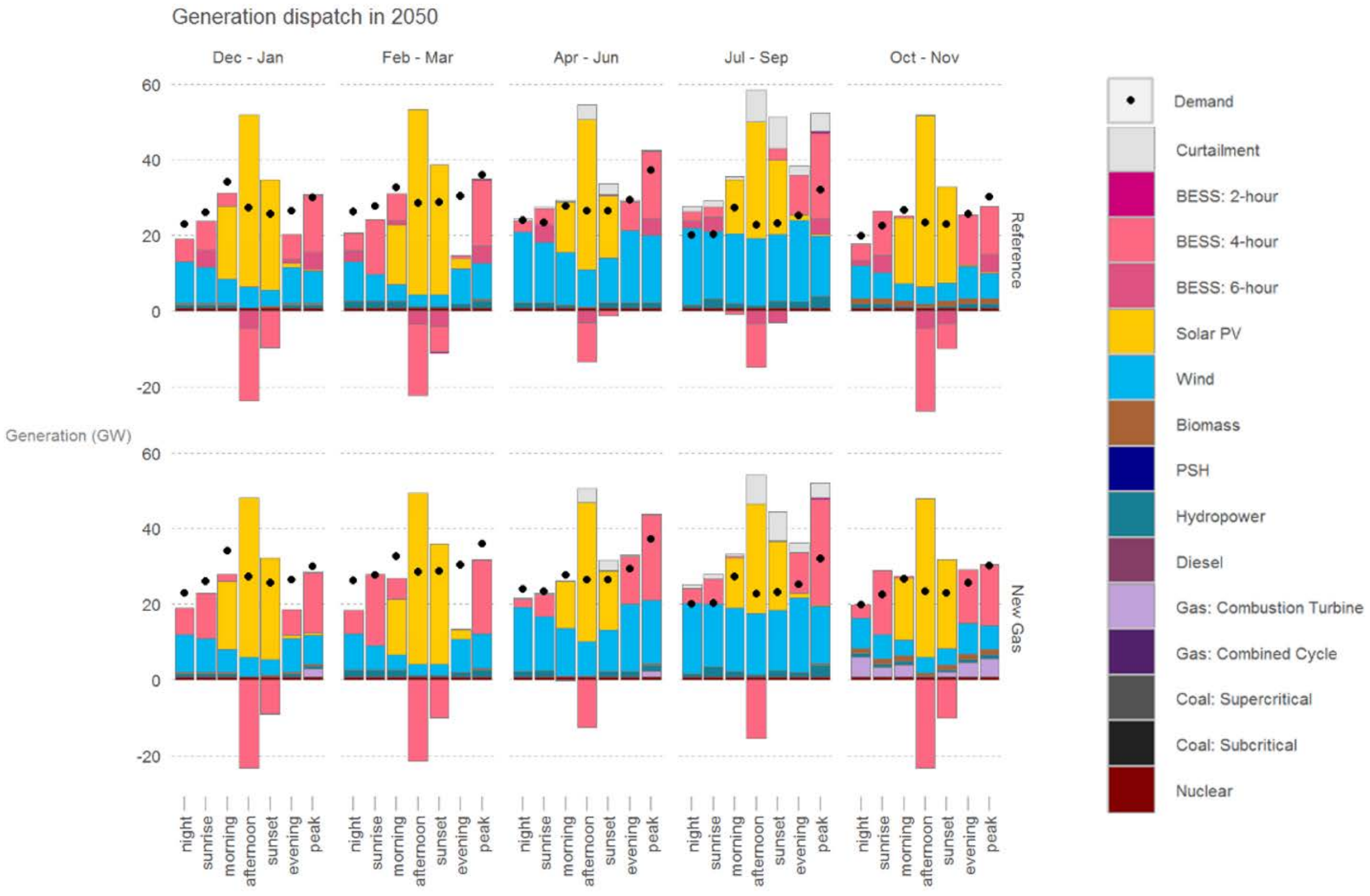

Figure 10. Reference versus New Gas scenario: Generation dispatch and demand in Karnataka for time-slices and seasons in 2050

4.3 Reduced PSH Cost

Of the Indian states, Karnataka has the third-largest capacity of hydropower, at 3689 MW as of June 2022 (Ministry of Power 2022). As a result of its hydropower resource and increasing share of VRE, the state government is interested in developing PSH to provide energy storage and other grid services (Nagarjun 2021). In the Reference scenario, investments in new PSH or upgrades to PSH (e.g., upgrading or retrofitting an existing storage hydropower site to have pumped storage capabilities) are not found to be cost-effective at the Reference price of 9.9 crore per MW in 2020 falling to 9.3 crore per MW in 2050.[3] Instead, the state's flexibility needs are met through investments in BESS technologies, interstate electricity trade, and VRE curtailment.

Investment costs for PSH are site-specific and can vary widely among projects. The Reduced PSH Cost scenarios investigate the impact of different capital cost assumptions for PSH and upgrades to PSH on the cost-competitiveness of these technologies vis-à-vis other sources of flexibility and generation. Figure 11 compares the capacity outcomes for different capital cost reduction scenarios for PSH and upgrades ranging from a 20% reduction (PSH20) to a 50% reduction (PSH50) by 2050 compared to the Reference scenario's default cost trajectory.

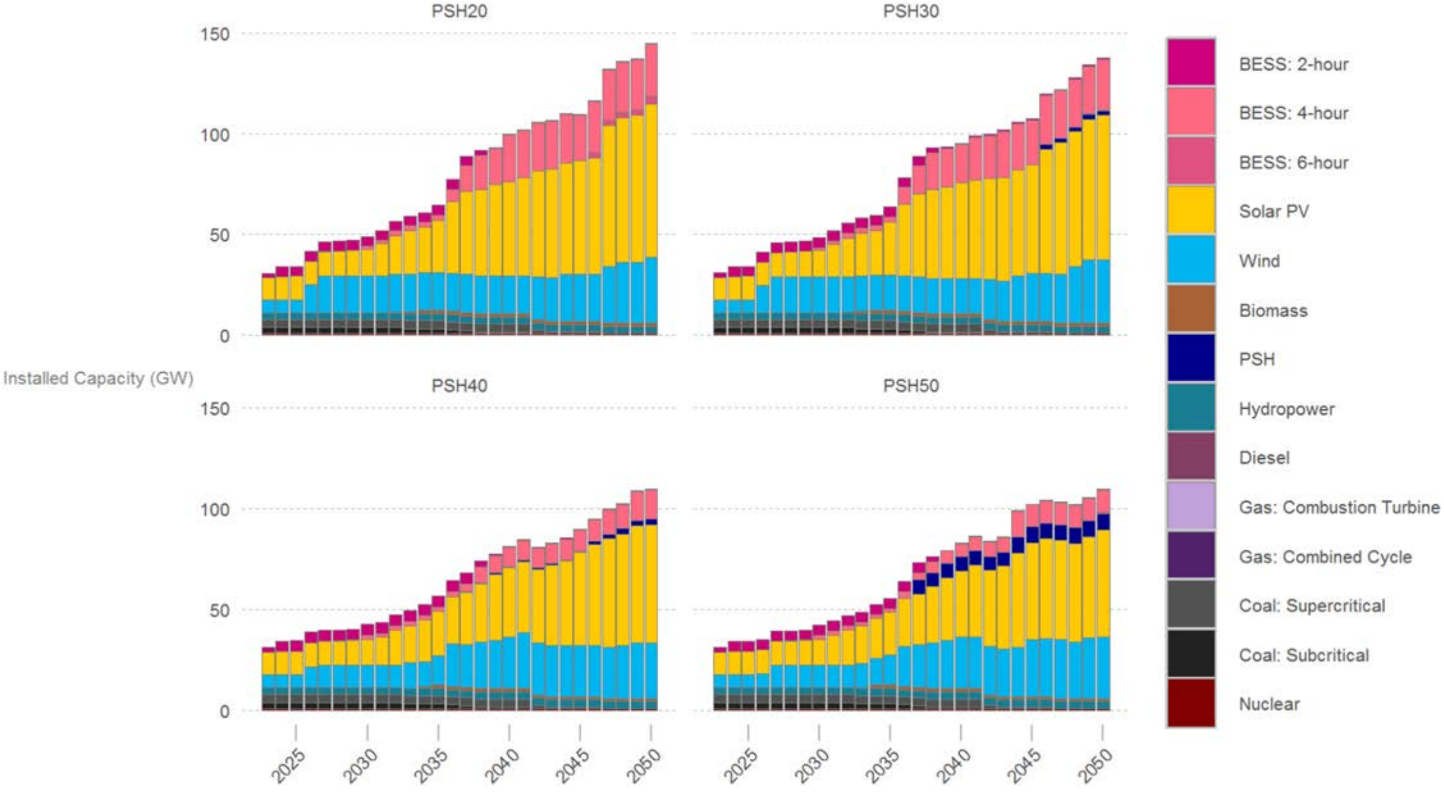

Figure 11. Reduced PSH Cost scenarios: Installed capacity of generation technologies in Karnataka

Note: The PSH scenarios refer to assumed reductions in PSH capital costs relative to the Reference scenario (e.g., PSH20 assumes costs are 20% lower, PSH30 assumes costs are 30% lower, etc.).

The results show that PSH technologies would need to achieve capital cost reductions of more than 20% by 2050 from current trend estimates, falling to less than 7 crore per MW to be cost-competitive with other technologies in the medium- to long-term. In the PSH30 scenario, investments in PSH are economic by 2045 at an assumed capital cost of 6.6 crore per MW. If further cost reductions are achieved (PSH50), PSH investments are competitive as early as 2035 at a capital cost of 6.5 crore per MW. Increased PSH capacity complements increased deployment of wind over solar PV and BESS. Across the Southern region, the PSH50 scenario

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[3] One crore equals 10 million Indian rupees (INR).

results in an 11% (28 GW) increase in wind capacity and a 6% (10.2 GW) decrease in solar PV capacity by 2050 compared to the Reference scenario.

Proposals for future PSH development indicate these costs could be achievable for some sites in Karnataka. The 2000 MW Sharavathy Pumped Storage Project proposed by Karnataka Power Corporation Limited is estimated to cost 2.5 crore per MW due to the minimal civil works involved (Mongabay 2020). These projects could provide additional generation and help shift output from wind and solar PV to meet demand. This study did not model specific sites and follow-on studies can use site-specific costs and project details to further investigate the scale of cost-competitive PSH for Karnataka.

In the PSH50 scenario in 2050, PSH charges during the afternoon and sunset periods during December–January and February–March and primarily serves load during the peak time-slices in all seasons (Figure 12).

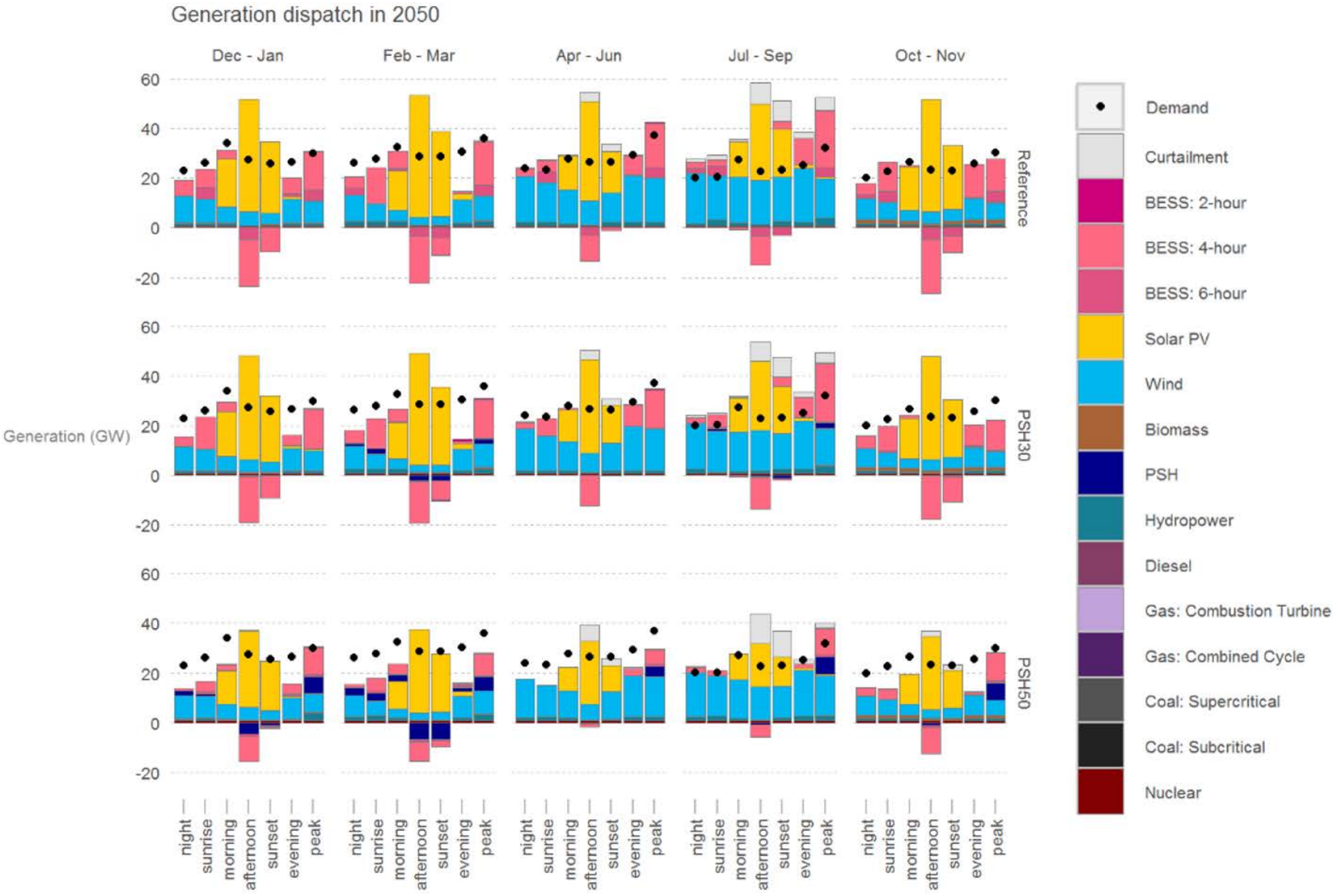

Figure 12. Reference versus Reduced PSH Cost scenarios: Generation dispatch and demand in Karnataka for time-slices and seasons in 2050

Increased wind deployment across the Southern region that accompanies PSH investments enables Karnataka to meet more demand through imports from neighboring states rather than build new solar PV and BESS capacity within the state. In 2050, electricity demand met by imports increases from 5% to 20% and total generation exported decreases from 9% to less than 1%, compared to the Reference scenario.

5 Demand-Side Scenarios

The demand-side scenarios investigate the impacts of changes in demand due to different factors (e.g., policies to shift agriculture load or consumer behavior that increases cooling loads) while keeping the same supply assumptions used in the Reference scenario. Therefore, the following results convey how the least-cost generation portfolio is sensitive to potential changes in electricity consumption.

5.1 Agriculture Load Shifting

Agriculture is the largest end use of electricity in the state, accounting for 39% of annual energy sales in fiscal year 2020 (KERC 2021).[4] The share of total electricity sales from agriculture is projected to decline in Karnataka through 2050 because the projected growth rate of agriculture demand is lower than the projected growth rate for total demand for all of India (Sreenivas et al. 2021). Karnataka is already shifting agriculture loads, which primarily consist of irrigation pumps, to midday to take advantage of peak solar PV generation (Abhyankar et al. 2021). However, the Reference scenario does not capture these recent shifts in agriculture loads because it uses 2014 hourly demand data as its baseline. Thus, the purpose of this scenario is to examine the sensitivity of the least-cost generation mix to agriculture load shifting.

In the Agriculture Load Shifting scenarios, 5% (LoadAgr5) and 10% (LoadAgr10) of agriculture electricity demand is shifted from the peak time-slice to the afternoon time-slice in all seasons and for all years analyzed. The afternoon time-slice contains more hours than the peak time-slice. As a result, the increase in demand in the afternoon period in absolute terms (MW) is lower than the corresponding decrease in demand in the peak period because the energy that is shifted is spread over more hours. This is depicted in Figure 13, which displays the agriculture electricity demand in each time-slice in the autumn season (October–November) in 2025 for both the Reference and LoadAgr10 scenarios. In both scenarios, total energy consumption is the same. It is important to note that the "peak" time-slice is determined based on national, not state-specific, peak demand. Karnataka's peak demand aligns with the nationally determined peak time-slice for all months of the year except December–January, during which the state's electricity demand is highest in the morning.

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[4] The fiscal year (FY) in India runs from April 1 to March 31. For example, FY 2020 started on April 1, 2019 and ended on March 31, 2020.

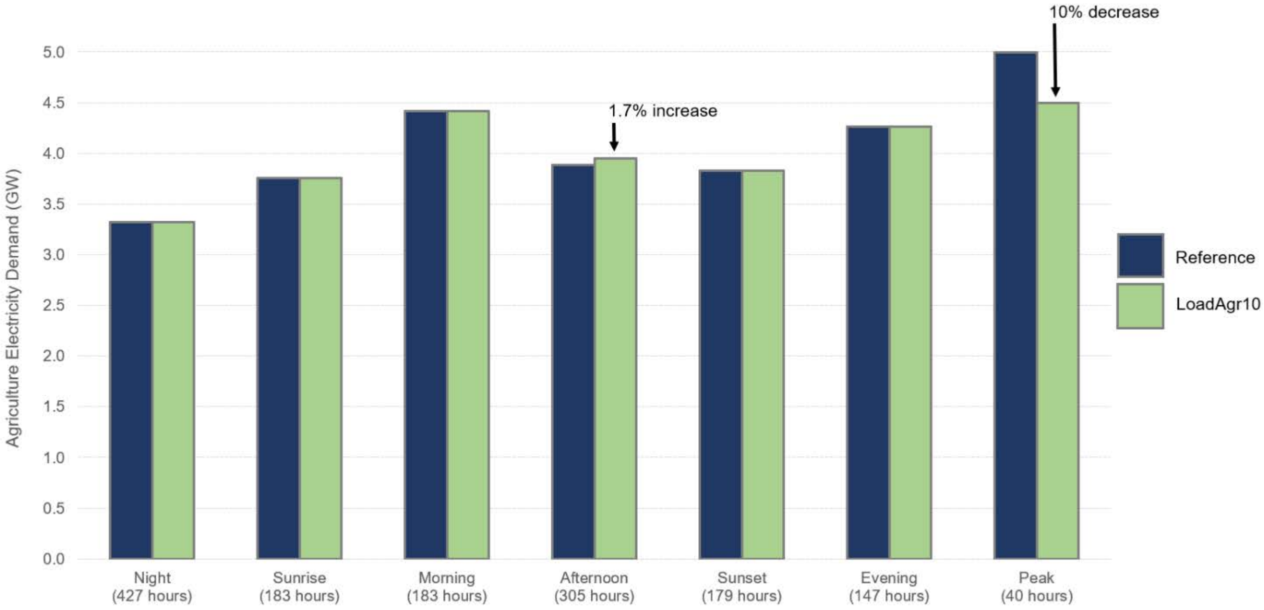

Figure 13. Reference versus LoadAgr10 scenario: Agriculture demand in each time-slice in autumn season (October–November) in 2025

In the LoadAgr5 and LoadAgr10 scenarios, shifting agriculture load from the evening peak to the daytime results in reduced investments in wind for most of the modeled years because less wind generation, which tends to be coincident with evening demand, is needed to meet a lower peak demand (Figure 14).

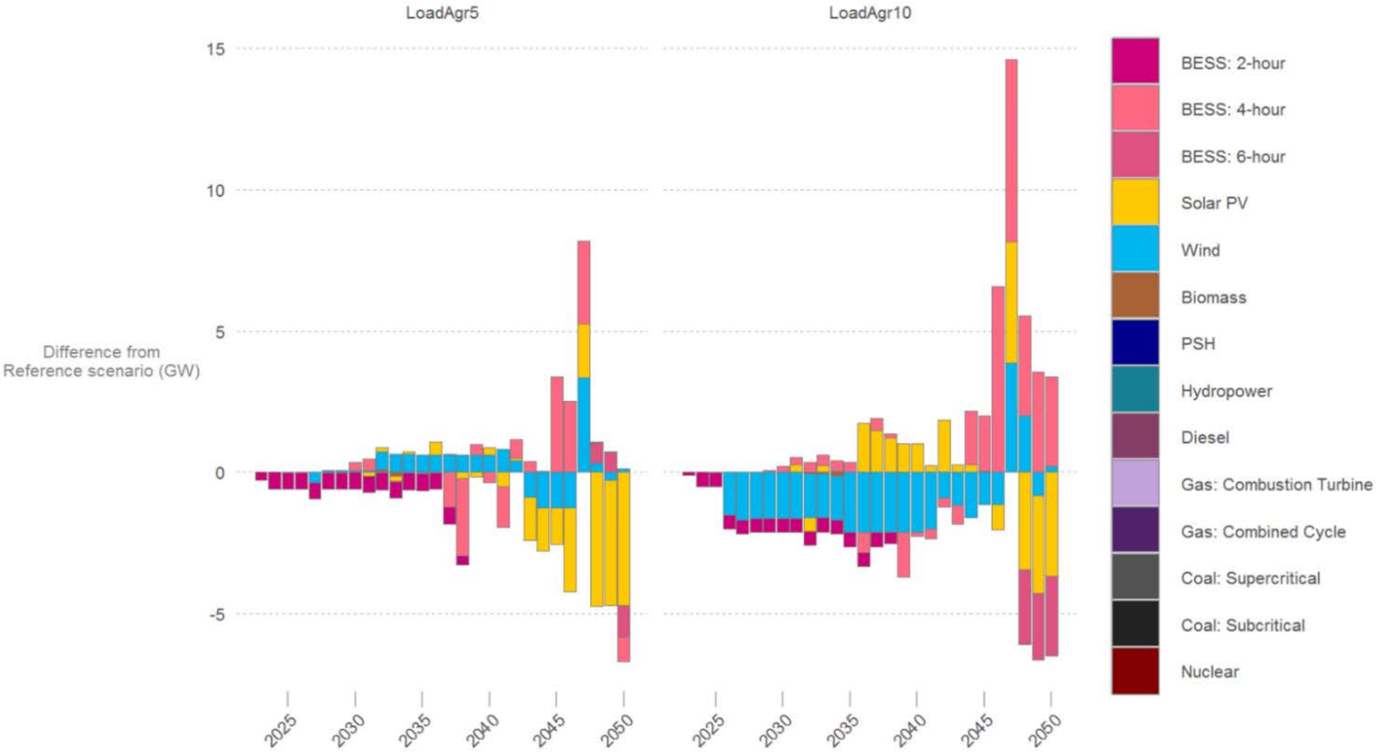

Figure 14. Agriculture Load Shifting scenarios: Difference in installed capacity of generation technologies compared to Reference scenario

There is also less investment in shorter-duration BESS, particularly 2-hour BESS in favor of 4-hour BESS. The impact on solar investments is mixed and evolves over time. In the medium-term, investments in solar PV increase to meet the increase in coincident demand during the afternoons. However, by 2050, these results suggest that perhaps the lower demand during the peak time-slices plays a more prominent role and reduces the need for solar PV and storage to meet peak demand. Instead, Karnataka relies more on electricity generated in neighboring states to meet demand throughout the year. In this study we assume neighboring states are not implementing similar agriculture load shifting programs; if they are pursing similar programs, this could impact opportunities for imports.

Agriculture load shifting decreases the estimated net system costs for Karnataka over the model period (Table 6). The net cost savings per unit of energy shifted (crore/GWh) give a rough estimate of the value of agriculture load shifting in the state. Though both scenarios result in lower system costs, the net savings per unit of agriculture load shifted is higher for the LoadAgr5 scenario, suggesting that there are diminishing returns to shifting electricity demand from peak to off-peak periods. In either case, the savings in excess of 4 crore per GWh could offset the cost of new generation capacity.[5]

Table 6. Agriculture Load Shifting Scenarios: Cost Reductions Compared to Reference Scenario

Cumulative Metric from 2020-2050 Model Period	LoadAgr5 Scenario	LoadAgr10 Scenario
Total energy shifted (GWh)	2,394	4,789
Total cost savings compared to Reference scenario[a] (crore)	25,600 (2.0% reduction)	21,000 (1.7% reduction)
Increase in net imports (GWh)	16.0	85.6
Cost of additional imports[b] (crore)	9.9	53.1
Net cost savings compared to Reference scenario (total minus imports) (crore)	25,590	20,947
Net cost savings/energy shifted (crore/GWh)	10.7	4.4

[a] The total cost consists of fuel costs, transmission capacity costs, generation capacity costs, fixed operation and maintenance (O&M) costs, and variable O&M costs.

[c] The cost to purchase imports is assumed to be 6.2 INR/kWh based on the Fiscal Year (FY) 2020 average cost of electricity supply ("Average Cost of State Electricity Supply in India from Financial Year 2009 to 2020 (in Indian Rupees per Kilowatt Hour)," Statista, https://www.statista.com/statistics/808201/india-cost-of-state-electricity-supply). We do not attempt to forecast the purchase cost of imports to 2050.

5.2 Increased Cooling Load

The Increased Cooling Load scenarios analyze the impacts of an increase in both residential and commercial cooling demand. For the Commercial Cooling scenario, the electricity demand in the morning and afternoon time-slices is increased by 5% in the spring (February–March) and 10% in the summer (April–June) for all years compared to the Reference scenario. This scenario assumes an increased uptake of air conditioning appliances in commercial buildings, primarily

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[5] The cost of shifting energy in this scenario is assumed to be zero, which might not accurately reflect the total costs required to enable this shifting.

increasing electricity consumption during the day. For the Residential Cooling scenario, the demand in the peak and sunset time-slices is increased by 5% in the spring and 10% in the summer for all years. This scenario assumes an increased uptake of air conditioning in residential buildings, primarily increasing electricity consumption in the evening. The purpose of these scenarios is to assess the sensitivity of the cost-optimal generation mix to higher cooling loads, which are approximated by an increase in demand during certain time-slices and seasons. Karnataka is likely to see these demand trends due to a combination of rising temperatures and economic growth. Annual electricity demand only increases by 2% by 2050 in the combined Increased Cooling Load scenarios, because demand is higher only during a subset of time-slices for certain seasons (spring and summer).

Compared to the Reference scenario, the total installed capacity in 2050 decreases for both cooling cases, but this trend is more pronounced for the Residential Cooling scenario (Figure 15). In the Commercial Cooling scenario, the 2050 power sector has slightly more wind and 6-hour BESS and slightly less solar PV and 4-hour BESS. In the Residential Cooling scenario, the 2050 power sector has less wind, solar PV, and 6-hour BESS.

Figure 15. Increased Cooling Load scenarios: Difference in installed capacity of generation technologies compared to Reference scenario

This reduction in installed capacity, despite an increase in demand, results in an increase in electricity imports for both Increased Cooling Load scenarios in 2050 (Figure 16). In the Residential Cooling scenario, for instance, 8% of annual demand in 2050 is met by imports compared to 5% in the Reference scenario.

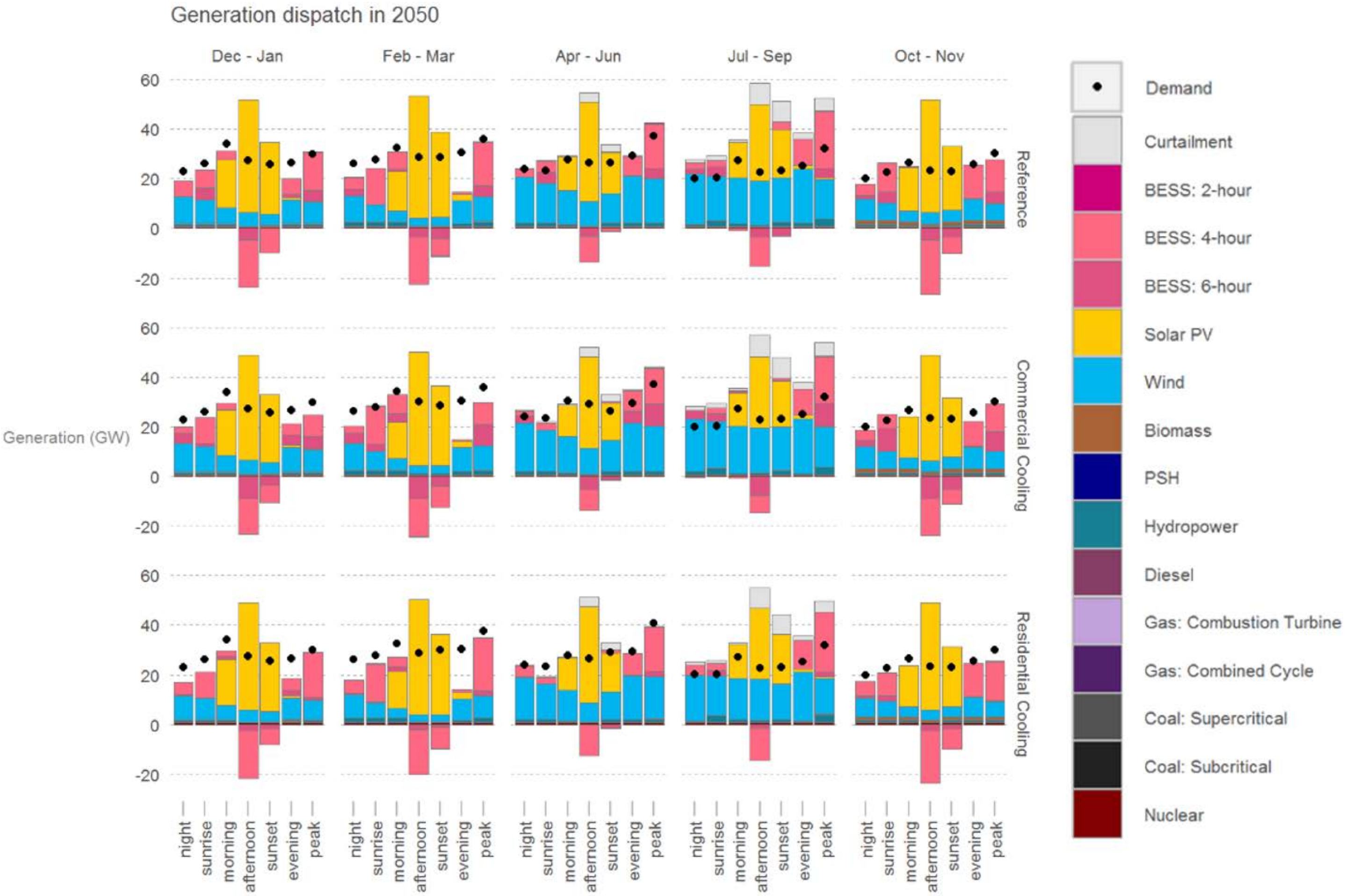

Figure 16. Reference versus Increased Cooling Load scenarios: Generation dispatch and demand in Karnataka for time-slices and seasons in 2050

This shift happens because the modeled increase in cooling demand only occurs in Karnataka, and only occurs during certain seasons and time-slices. Therefore, it is more cost-effective for in-state demand to be met by out-of-state generators with excess capacity as opposed to building new generation to serve the increased demand for only specific portions of the year. However, if Karnataka is experiencing higher cooling demand, there will likely be correlated changes in demand in neighboring states. Thus, increased coordination between state planners and operators may be required to meet changes in future demand patterns.

6 Conclusions

The power sector in Karnataka is on track to undergo significant changes over the coming decades, in terms of both supply and demand. National and state-level policies, as well as falling technology costs, drive significant investments in wind, solar PV, and BESS in the model. These wind and solar PV investments could be economic at levels far beyond Karnataka's target for 2027. New investments in nuclear are uneconomic at current cost trajectories and the remaining fossil-fuel capacity is retired by mid-century.

The results from this long-term assessment are relevant for a variety of decision makers. The following key insights from this study can help inform Karnataka's ability to plan its power system in a way that cost-effectively meets policy goals and anticipates changes to demand:

- The least-cost mix of generation resources to meet forecasted electricity demand and policy constraints by 2050 consists primarily of solar PV (52%), wind (23%), and BESS (21%), with smaller shares of biomass, hydropower, and nuclear.

- Without national and state-level policies that set renewable energy goals and ban investments in new thermal plants, coal retirements are delayed and 10 GW of natural gas capacity is deployed, assuming adequate supply infrastructure.

- Investments in PSH, either as new plants or as upgrades, are cost-competitive if capital cost reductions of at least 20% by 2050 can be achieved compared to current trajectories. Proposals for projects in Karnataka indicate these reductions can be realized for some sites, and this study did not include site-specific costs in the model. This study also did not investigate scenarios with increased costs for battery technologies; this could also increase the cost-competitiveness of PSH.

- Shifting agriculture demand from peak load periods to afternoon periods can result in system-wide cost savings and more effective utilization of solar PV capacity. Though there may be diminishing returns regarding the value of this load shifting, the cost savings likely exceed the cost of new generation.

- Increases in cooling demand, from the residential or commercial sector, have the potential to increase imports in 2050 in a cost-optimal generation mix. However, if neighboring states are also facing higher cooling demand, increased coordination between state planners and operators may be required in addition to new capacity.

The model developed for this study can provide a framework for recurring planning studies with more refined and updated inputs.

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Appendix A. Additional Model Assumptions

This appendix details additional assumptions used in the ReEDS-India capacity expansion model for this study.

A.1 Electricity Supply Investments

Table A-1 lists the capital cost, fixed cost, and plant lifetime assumptions by technology. The plant lifetime is the maximum operating age of the plant, after which it must be retired or refurbished.

Table A-1. 2022 Capital Cost and Plant Lifetime Assumptions for Supply Technologies

Technology	2022 Capital Cost (crore/MW)	Fixed O&M (crore/MW/year)	Plant Lifetime (years)
BESS: 2-hour	4.2	0.11	15
BESS: 4-hour	7.0	0.18	15
BESS: 6-hour	9.9	0.25	15
BESS: 8-hour	12.7	0.32	15
BESS: 10-hour	15.5	0.39	15
Gas: Combined Cycle	5.6	0.16	55
Biomass: Cogeneration Bagasse	5.7	0.16	45
Gas: Combustion Turbine	4.9	0.12	55
Diesel	3.9	0.09	55
Distributed PV (DPV)	9.1	0.10	30
Hydropower: Pondage	10.0	0.19	100
Pumped Storage Hydropower (PSH)	9.9	0.29	100
Hydropower: Run-of-River	6.5	0.21	100
Hydropower: Storage (reservoir)	9.9	0.29	100
Nuclear	11.7	0.85	100
Coal: Subcritical	6.4	0.49	25
Coal: Supercritical	15.1	0.42	25
Upgrade to PSH	1.9	0.29	100
Utility-Scale PV (UPV)	4.6	0.13	30
Waste Heat Recovery	5.6	0.24	45
Wind: Land-Based	5.8	0.25	25

For all technologies, both mature and emerging, declines in capital costs are assumed over time as manufacturers and developers gain experience with the technologies. We adopt the rates of decline used in NREL's Annual Technology Baseline mid-case estimates (NREL 2021). Figure A-1 shows the anticipated changes in capital costs over the model period for each candidate technology.

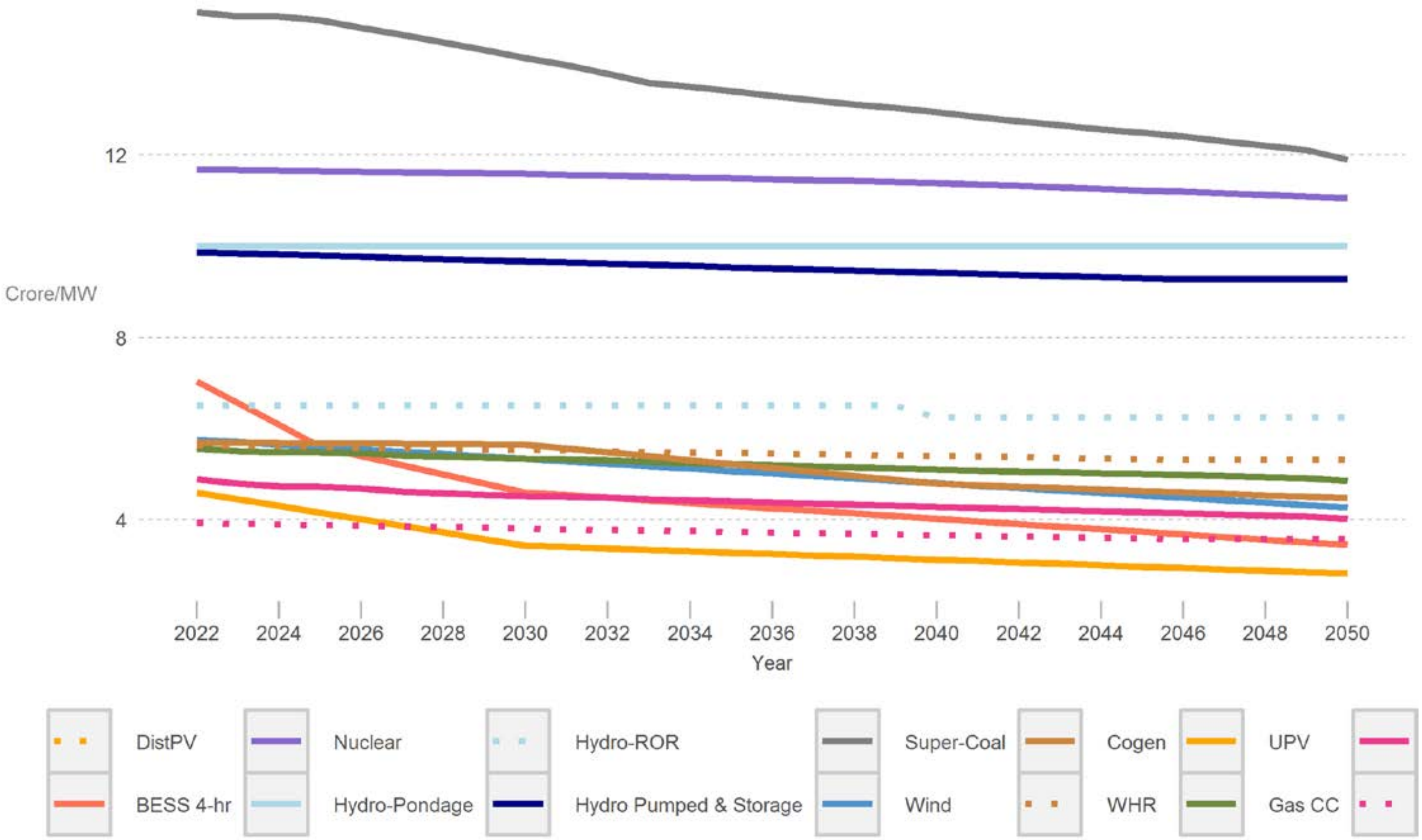

Figure A-1. Changes in capital costs for generation technologies

The investment constraints represent policy, resource, or technical criteria that may influence investment outcomes. We impose four types of investment constraints on generation additions: (1) first year for economic capacity additions, (2) absolute growth limits, (3) relative growth limits, and (4) geographic diversity requirements.

The first year for endogenous capacity additions is the initial year when new capacity can be built based on economic criteria. Before the first year, only planned additions can be added. For all technologies except wind and solar, we assume projects not already underway will not be complete by 2023. Therefore, these technologies cannot begin economic builds until 2023.

The absolute growth limit represents the state-wise capacity limits over the entire model period on hydropower, biomass, and waste heat recovery technologies based on their estimated potential (CEA 2018b; CEA 2018c). Table A-2 contains the absolute growth limits for each technology type in Karnataka.

Table A-2. Absolute Growth Limits on Installed Capacity for Select Technologies (MW)

Technology	Capacity Limit (MW)
Biomass: Cogeneration Bagasse	1,131
Hydropower: Pondage	507
Hydropower: Run-of-River	281
Hydropower: Storage (reservoir)	4,320
Pumped Storage Hydropower	7,900
Waste Heat Recovery	450

Finally, we use relative growth and geographic diversity constraints to prevent unrealistic rates of capacity growth in any single year or location. All technologies except BESS are constrained with a 50% year-over-year limit of growth relative to installed capacity in the previous year. Under the geographic diversity constraint, investments in wind and solar must be geographically dispersed such that no more than 15% of annual additions are placed in a single resource region. This constraint is based on national wind and solar additions; at the state level, the concentration of wind and solar investments in a single resource region may exceed 15%.

A.2 System Operations

ReEDS uses a reduced form-dispatch where aggregated generation technology types, rather than individual units, are dispatched to meet requirements for operating reserves and electricity demand in each time-slice. Table A-3 (page 30) presents the operational characteristics and constraints designed to capture the cost and performance characteristics of each technology type. Unless otherwise stated, all operating parameters are taken from Palchak et al. (2017) and Rose et al. (2020). DPV, UPV, and wind are assumed to have no variable cost or ramping and loading constraints; outage rates for these technologies are captured by capacity factor assumptions.

The operating constraints represent technical and resource-based limits on how technologies may be dispatched. These constraints include (1) seasonal limits on hydropower generation, (2) limits on gas fuel supplies, (3) minimum loading for natural gas CC plants, and (4) seasonal minimum loading limits.

Seasonal rainfall patterns directly impact potential generation from hydropower plants throughout the year. To account for variations in water available for hydropower generation, we include seasonal capacity factors for each type of hydropower generator. Using the Central Electricity Authority's monthly generation data for hydropower plants for 2015–2016 and 2016–2017 and 16 years of annual generation data (CEA 2016), we calculate average seasonal capacity factors for each plant in the report. We combine these data with data from the power plant database from Palchak et al. (2017) and data from other publicly available sources to classify each plant as run-of-river, pondage, storage, or pumped, and we then calculate the average capacity factor by plant type for Karnataka (Table A-4, page 31).

Table A-3. Technology Operating Parameters

Technology	2022 VOM[a] Cost (INR/kWh)	2022 Heat Rate (GJ/MWh)	Ramping Limit (MW/min)	Min Loading Fraction	Planned/Unplanned Outage (%)
BESS: 2-hour	—	—	15.3	0.00	0/0
BESS: 4-hour	—	—	15.3	0.00	0/0
BESS: 6-hour	—	—	15.3	0.00	0/0
BESS: 8-hour	—	—	15.3	0.00	0/0
BESS: 10-hour	—	—	15.3	0.00	0/0
Gas: Combined Cycle	2.33	9.33	3.4	0.50	2.4/8.5
Biomass: Cogeneration Bagasse	4.87	12.30	0.5	0.50	2.4/8.5
Gas: Combustion Turbine	2.60	10.26	1.8	0.00	4.1/4.3
Diesel	2.08	11.48	1.8	0.50	4.1/4.3
Hydropower: Pondage	—	—	10.5	0.00	6.7/3.9
Pumped Storage Hydropower (PSH)	—	—	15.3	0.20	6.7/3.9
Hydropower: Run-of-River	—	—	5.4	0.00	6.7/3.9
Hydropower: Storage (reservoir)	—	—	8.2	0.00	6.7/3.9
Nuclear	2.50	—	1.7	1.00	2.3/8.3
Coal: Subcritical	2.07	11.12	3.8	0.55	5.0/10.0
Coal: Supercritical	0.68	8.94	10.2	0.55	4.0/8.0
Upgrade to PSH	—	—	15.3	0.20	6.7/3.9
Waste Heat Recovery	3.77	—	0.5	0.00	5.0/8.5

[a] variable operation and maintenance

Table A-4. Seasonal Capacity Factors for Hydropower Technologies

Plant Type	Dec–Jan	Feb–Mar	Apr–Jun	Jul–Sept	Oct–Nov
Hydropower: Pondage	0.12	0.30	0.39	0.18	0.12
Pumped Storage Hydropower (PSH)	0.38	0.41	0.20	0.47	0.47
Hydropower: Run-of-River	0.24	0.17	0.24	0.49	0.43
Hydropower: Storage (reservoir)	0.18	0.38	0.28	0.39	0.22

National fuel supply limits of 20 million metric standard cubic meters per day are imposed on gas technologies based on historical domestic and imported gas supplies. We assume no change in available gas supplies from 2020 to 2050 (CEA 2019). Gas fuel for new plants is assumed to come from imported liquified natural gas (LNG) sources. Gas plant operations in India are limited by long-term fuel supply contracts. A gas supply contract typically takes the form of a take-or-pay agreement, wherein daily gas delivery volumes are agreed on several months or years in advance of actual delivery. This type of fuel supply agreement prevents the gas fleet from adjusting unit commitment decisions based on daily, weekly, or seasonal variations in energy demand. To approximate the contractual limitations on the timing of gas fuel supply, the fleet of combined-cycle gas plants in each BA must generate in all times and seasons in a given year or not at all.

The constraint on timing of fuel supply is not imposed on open-cycle gas plants (i.e., gas: combustion turbine plants). We assume gas CT plants can enter flexible fuel supply contracts that enable delivery of fuel when it is needed. We also assume necessary upgrades are made to the gas pipeline infrastructure, including compressor stations and pipeline network expansions, to enable flexible timing in the delivery of gas fuel for peaking plants. As with other technologies, the cost of new infrastructure investments to enable fuel delivery are assumed to be reflected in the plant’s delivered fuel cost.

Finally, we impose minimum generation limits to restrict unrealistic plant cycling within each season. For any given season and BA, technologies that are dispatched must generate at or above their minimum loading level described in Table A-3 (page 30). This constraint prevents a situation where, for example, thermal capacity is dispatched during the morning peak, turned down to zero midday, and dispatched again to meet evening peak demand.

A.3 Transmission

Table A-5 contains the transmission capital cost assumptions for each BA in Karnataka. These costs are based on the investment cost for the highest voltage line in each BA. In Karnataka, these voltages are 765 kV and 400 kV. The final capital costs used in the model are obtained by dividing the per-kilometer costs by the average carrying capacity of the interstate lines for that voltage in each BA. The distance between BAs is estimated using the geographic coordinates of the largest population center of each BA.

Table A-5. Capital Costs for Select Transmission Voltages

BA	Highest Voltage Inter-BA Line (kV)	Capital Cost (Lakh/km)[6]	Transmission Cost (Lakh/MW-km)
Bagalkote	765	413	0.67
Bengaluru	400	124	0.54
Hassan	400	124	0.61
Kalaburgi	765	413	0.55
Mysuru	400	124	0.71
Tumakuru	400	124	0.58

A.4 Reliability

The assumptions for operating reserve costs and technology-specific contributions in Table A-6 are based on the U.S. ReEDS assumptions documented in Ho et al. (2021).

Table A-6. Operating Reserve Parameters

Technology	Cost for Providing Operating Reserve (INR/MW)	Contribution of Capacity to Operating Reserve Capacity
Coal: Subcritical	702	10%
Coal: Supercritical	1,053	10%
Diesel	281	20%
Gas: Combined Cycle	421	30%
Gas: Combustion Turbine	281	30%
Pumped Storage Hydropower (PSH)	140	100%
Hydropower: Storage (reservoir)	140	100%

A.5 Renewable Resource Supply Curves

We use supply curves for wind and solar to characterize the potential sites available for development, and we directly evaluate the investments in these generation sources. These supply curves are estimated from detailed weather data, geospatial data on exclusion areas and the existing transmission network, and financial assumptions about technology costs (for generation and/or substation upgrades) to arrive at a site-based levelized cost of electricity, including both resource-based and transmission cost considerations. For each site, hourly generation profiles are created to estimate generation, curtailment, and capacity credit for all wind and solar investments.

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[6] One Lakh is equal to one-hundred thousand Indian rupees (INR)

Solar and wind technologies in each gridded cell are assigned to classes based on the quality of the resource (i.e., irradiance or wind speed) at a specific location. Solar resources are grouped into nine resource classes and wind resources are grouped into three. Table A-7 summarizes the resource classes for solar and wind based on annual average resource quality.

Table A-7. Summary of Solar and Wind Resource Classes

Class	Solar (kWh/m²-day)	Wind (m/s)
1	≤ 3.5	≤ 8
2	3.5–4.0	8–9
3	4.0–4.5	> 9
4	4.5–5.0	
5	5.0–5.5	
6	5.5–6.0	
7	6.0–6.5	

Based on these classes, Figures A-2 through A-4 summarize the wind and solar supply curves, which represent the total cumulative capacity that could be built for the Karnataka region.

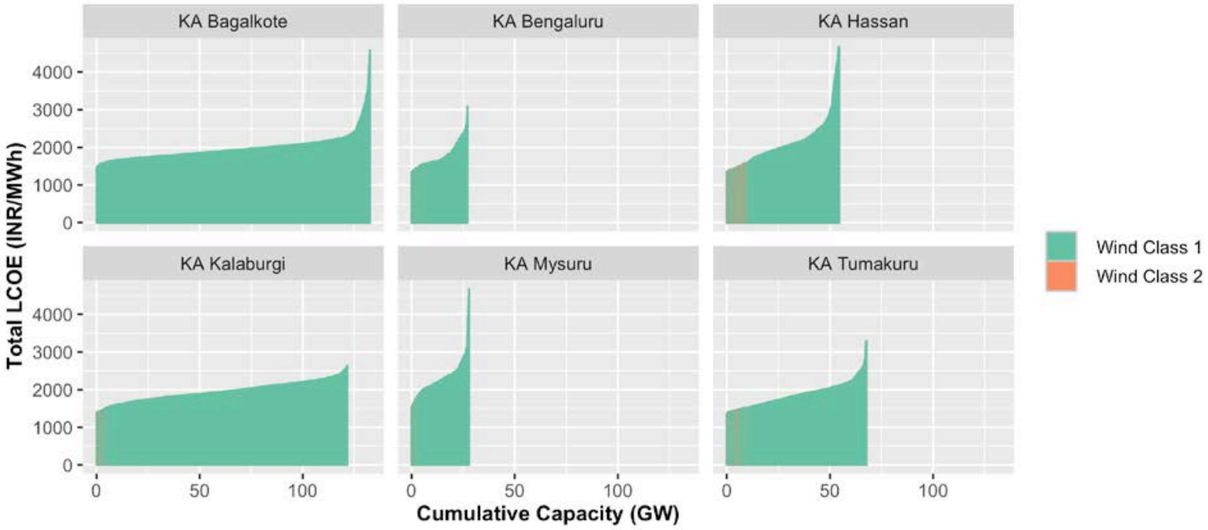

Figure A-2. Wind resource supply curve

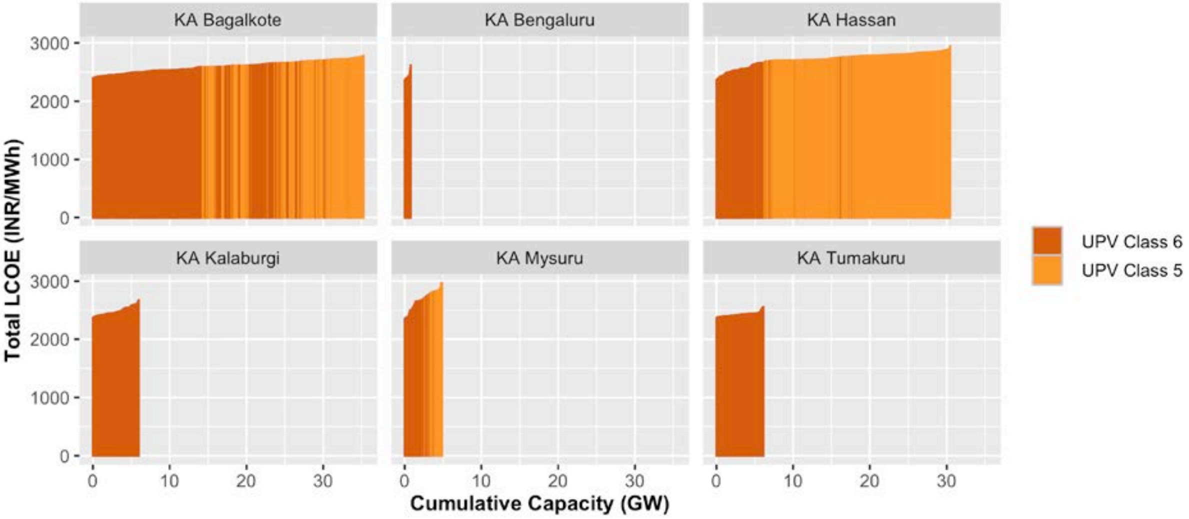

Figure A-3. UPV resource supply curve

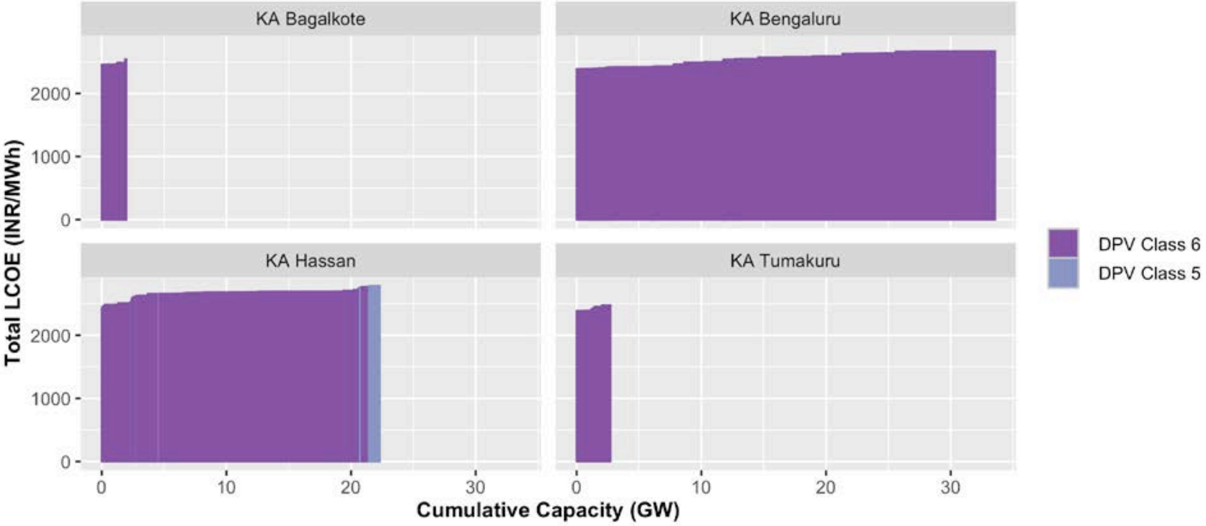

Figure A-4. DPV resource supply curve

Areas with stronger renewable resources (i.e., higher wind speeds or solar irradiance) tend to have lower levelized cost of electricity values, meaning these areas are less expensive to develop. However, this is not always the case, as can be seen in Figures A-2 through A-4 where, for example, areas with strong wind resources (Wind Class 2) have higher levelized cost of electricity values compared to areas with lower wind resources (Wind Class 1). This can occur if no transmission is available in the vicinity and the assumed cost for grid integration is high. This example demonstrates the value of including detailed geospatial data for both renewable resources and grid infrastructure to improve the estimated cost of developing a particular site.

Using this information, each of Karnataka’s 30 resource regions is assigned a maximum developable capacity (MW), interconnection cost (INR/MW), and capacity factor by time-slice and hour for every applicable resource class of wind, UPV, and DPV.