Impacts of Renewable Energy and Green Hydrogen Policies on Uttar Pradesh's Power Sector Future

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National Renewable Energy Laboratory

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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.[1]

Other publications in this series include:

- *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)
- *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)
- *Role of Renewable Energy, Storage, and Demand Response in Karnataka's Power Sector Future* (Joshi, Rose, and Chernyakhovskiy 2022)
- *Opportunities for Renewable Energy, Storage, Vehicle Electrification, and Demand Response in Rajasthan's Power Sector* (Chernyakhovskiy et al. 2022)
- *Evaluation of Air Quality Benefits of Renewable Electricity and Green Hydrogen Policies in Uttar Pradesh* (Ravi et al. 2024)

Holistically, this work helps identify the necessary investment and operational strategies to achieve India's clean energy goals and equips key institutions and decision makers with the tools, data, and resources to inform and implement these strategies.

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[1] See https://www.nrel.gov/international/india-renewable-energy-integration.html.

Acknowledgments

The authors wish to thank the Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA), as well as Uttar Pradesh Power Corporation Limited, for their collaboration, inputs, and insightful feedback that helped facilitate and improve this study. Thanks to Sonika Choudhary, Arjun Gupta, Ankur Malyan, Jagabanta Ningthoujam, and Aaron Shwartz at RMI for their assistance with coordination, data collection, scenario development, green hydrogen demand modeling, and results interpretation throughout the course of the project. Stakeholder and project meetings to inform this report were conducted in New Delhi, India, in December 2022 and in Lucknow, India, in January 2023, July 2023, and February 2024.

Thanks to Sophie-Min Thomson and Travis Williams at the National Renewable Energy Laboratory (NREL) for conducting the renewable energy resource assessment for Uttar Pradesh. Thanks to Stuart Cohen, Vikram Ravi, Amy Rose, and Jaquelin Cochran (NREL) for their thoughtful reviews and feedback. And finally, thanks to Isabel McCan, Nicole Leon, and Liz Breazeale (NREL) for communications, editing, and design support. Any errors or omissions are solely the responsibility of the authors.

List of Acronyms

BESS	battery energy storage system
CEA	Central Electricity Authority
DISCOM	distribution company
H_2	hydrogen
INR	Indian rupee
MMT	million metric tons
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PV	photovoltaic
RE	renewable energy
ReEDS	Regional Energy Deployment System
UPNEDA	Uttar Pradesh New and Renewable Energy Development Agency

Executive Summary

The power sector in Uttar Pradesh, India's most populous state and second-largest consumer of electricity, is poised to transform over the next few decades due to a combination of national and state-level policies impacting both the supply and demand of electricity. India has national targets of achieving 50% of its installed power capacity from non-fossil fuel resources by 2030, and India's Central Electricity Authority (CEA) revised its power sector reliability requirements.[2] India also launched the National Green Hydrogen Mission, which envisions green hydrogen production capacity of 5 million metric tons (MMT) per year by 2030 to develop a domestic green hydrogen industry for various sectors and export markets.[3] To align with these national goals, the Government of Uttar Pradesh has policies and plans to develop in-state solar photovoltaics (PV), pumped storage hydropower, and green hydrogen.

Power system policymakers and utilities in Uttar Pradesh are faced with the challenges of planning a system that incorporates increasing amounts of renewable energy and storage resources, meets rising electricity demand due to economic development and green hydrogen production, and satisfies operational and reliability requirements. To support these various objectives, the National Renewable Energy Laboratory (NREL), RMI, and the Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA) evaluated least-cost pathways for the state's power sector through 2050. NREL developed a capacity expansion model that identifies investment and operational decisions for every year (2023–2050) for all of India, with detailed representation of Uttar Pradesh, that provides a framework for recurring planning studies. The main insights from this study, described below, can also assist stakeholders in making policy and investment decisions. NREL also assessed the air quality co-benefits of the future power sector scenarios for Uttar Pradesh in an accompanying study (Ravi et al. 2024).

State-level policies and targets drive Uttar Pradesh's anticipated growth in solar PV and pumped hydropower in the near term.

In the Reference scenario that assumes no Uttar Pradesh-specific renewable energy policies, the state's power mix remains relatively static through 2030, with no additional capacity added. This result differs from the Renewable Energy (RE) Policy scenario, which includes state-level targets for solar PV (22 GW by 2027) and pumped hydro (12 GW by 2028). The comparison between the capacity mix for these two scenarios through 2030 is shown in Figure ES-1. In the RE Policy scenario, 1.5 GW of 2-hour battery energy storage systems (BESS) is installed by 2030, showing that although not a part of Uttar Pradesh's policies, in-state battery storage is a least-cost byproduct of the solar PV and pumped hydro buildout. Furthermore, as a result of these policies to diversify its generation mix and enhance its energy security, Uttar Pradesh's reliance on

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[2] The CEA revised its reliability requirements from ensuring that each grid region (Northern, Northeastern, Eastern, Southern, and Western) maintains a 15% planning reserve margin to ensuring that each state maintains a 7% planning reserve margin.

[3] This study assumes that "green hydrogen" refers to hydrogen production from electrolysis of water, using electricity that is generated by renewable energy resources (i.e., wind and solar PV), thus resulting in low or zero greenhouse gas emissions during production (Joshi, Chernyakhovskiy, and Chung 2022).

imports in 2030 drops from 184 TWh (84% of annual demand) to 152 TWh (70% of annual demand).

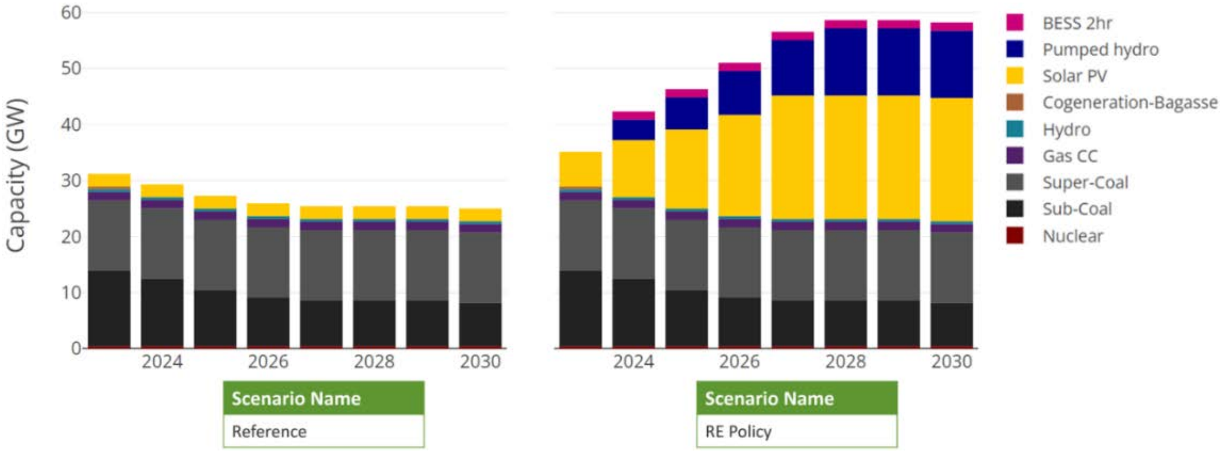

Figure ES-1. Reference vs. RE Policy scenario: Uttar Pradesh installed capacity (2023–2030)

Note: BESS 2 hr = BESS with a 2-hour maximum discharge duration, CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

In the long term, Uttar Pradesh could meet a large portion of its electricity demand from in-state wind resources.

While Uttar Pradesh has not traditionally been considered to have significant wind potential, results show that in-state wind resources could be cost-effective in the long term, and therefore stakeholders could start investigating wind resource potential in the state and encouraging its development through policies. In both the Reference and RE Policy scenarios, installed wind capacity grows significantly from 2030–2050, reaching almost 69 GW by 2050 (Figure ES-2).

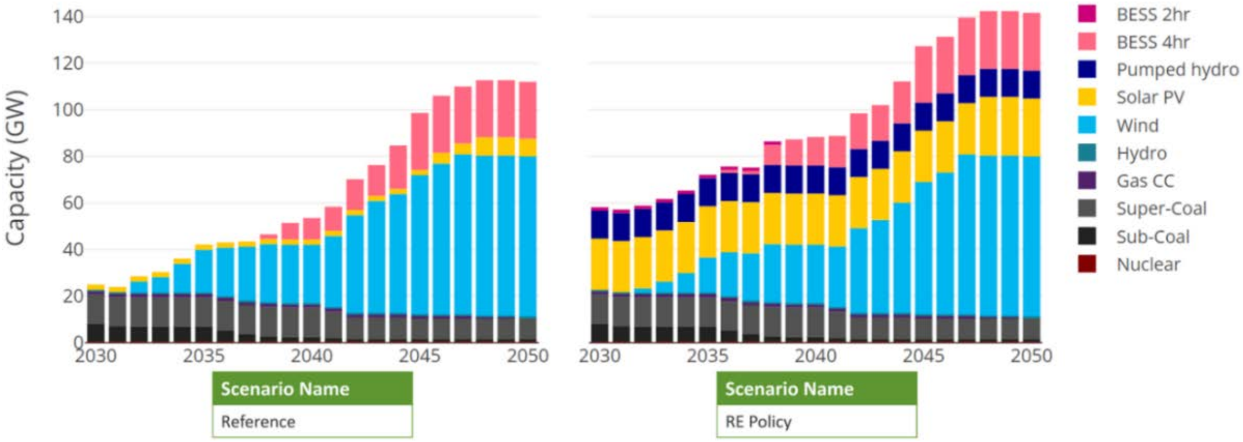

Figure ES-2. Reference vs. RE Policy scenario: Uttar Pradesh installed capacity (2030–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

In-state wind plays a major role in the power sector across all scenarios, with the potential to meet between 23% and 28% of annual electricity demand by 2050 without co-located renewables for green hydrogen production. Several factors contribute to this result:

- Wind technology costs are assumed to decline over time (Figure 5), making areas with lower wind speeds and capacity factors more viable for future development. This is because, unlike other assessments, the Regional Energy Deployment System-India (ReEDS-India) model does not contain a minimum wind speed or capacity factor cutoff. Wind capacity starts to be built in Uttar Pradesh roughly when the capital cost dips below 6 INR Crore/MW. As a comparison, battery storage capacity starts to be built in Uttar Pradesh roughly when the capital cost dips below 5 INR Crore/MW, and solar PV starts to be built economically (i.e., without policy mandates) roughly when the capital cost dips below 4 INR Crore/MW.
- India's high-wind states, such as Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Rajasthan, and Tamil Nadu, are expected to develop a large portion of the country's best wind resources by the mid-2030s, making wind power competitive in Uttar Pradesh during the later phases of India's wind development.
- A difference in assumptions might exist between this study and others regarding the availability and cost of land for wind development in Uttar Pradesh.

In summary, the wind resources in Uttar Pradesh, which are not commercially viable today, are thus not captured in present-day assessments but are potentially relevant in this forward-looking assessment (see Text Box 1 for further details).

Uttar Pradesh can more cost-effectively meet its anticipated electricity demand for green hydrogen production with out-of-state renewables.

Results show that Uttar Pradesh's anticipated electricity demand for green hydrogen production is met by the grid in the least-cost scenario, and thus can be supplied by in-state or out-of-state renewables. In 2030, the modeled increase in Uttar Pradesh's electricity demand for green hydrogen production (53 TWh due to 1.1 MMT of green hydrogen) results in an increase of in-state solar PV generation (1 TWh) as well as solar PV generation in all of India (55 TWh). In 2050, the increase in electricity demand due to green hydrogen more than doubles (110 TWh due to 2.3 MMT of green hydrogen), resulting in an increase of in-state (3 TWh) and nationwide (111 TWh) wind and solar generation. The national-level results are summarized in Figure ES-3, which shows the changes in generation triggered by the addition of green hydrogen demand in Uttar Pradesh in both 2030 and 2050. Although in-state renewable energy generation does not sufficiently increase to meet the additional electricity demand caused by green hydrogen production, Uttar Pradesh can meet this demand with additional out-of-state renewable generation. However, state policymakers can ultimately decide whether it is realistic to rely on electricity imports for most of Uttar Pradesh's green hydrogen production needs.

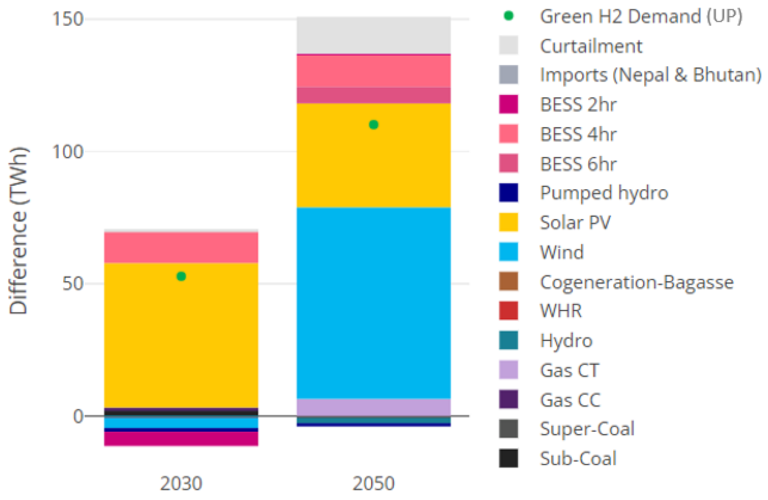

Figure ES-3. RE Policy, Baseline Green Hydrogen (H_2) scenario: Difference in all India generation compared to the RE Policy scenario, with Uttar Pradesh green hydrogen demand (2030 and 2050)

Note: UP = Uttar Pradesh, WHR = waste heat recovery, CT = combustion turbine, CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

Without co-location of renewables for in-state green hydrogen production, Uttar Pradesh increasingly relies on electricity imports and transmission interconnections.

In all scenarios except when renewables are co-located with green hydrogen production within Uttar Pradesh, the state relies increasingly on electricity imports. Imports, including hydropower from Nepal and electricity generated in other Indian states, serve 152 TWh (70%) of demand in the RE Policy scenario and 202 TWh (74%) of demand in the RE Policy, Baseline Green H_2 scenario in 2030. These numbers rise to 278 TWh (56%) and 367 TWh (61%) of demand by 2050, respectively. This trend is shown in Figure ES-4, which also displays the increase in annual electricity demand due to green hydrogen production. As a result of this heavy reliance on imports, transmission investments between Uttar Pradesh and Rajasthan range from 27 GW to 33 GW from 2030–2050.

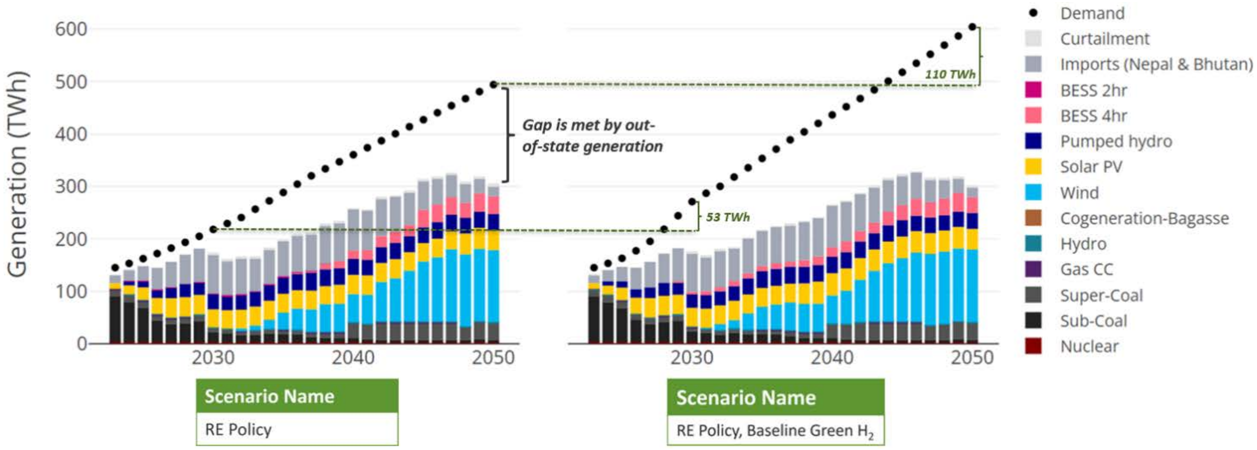

Figure ES-4. RE Policy vs. RE Policy, Baseline Green H_2 scenario: Uttar Pradesh annual generation and demand (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

In meeting its green hydrogen production targets, Uttar Pradesh needs to balance the trade-offs between imports and co-located renewables.

The two green hydrogen scenarios assessed in this study represent opposite ends of a spectrum of approaches to meet the electricity demand increase. At one end (RE Policy, Baseline Green H_2 scenario), Uttar Pradesh meets almost all of its electricity demand for green hydrogen production with out-of-state renewables, primarily from Rajasthan. The model results show this approach to be technically feasible and more cost-effective. At the other end (RE Policy, Baseline Green H_2, Co-Located RE scenario), Uttar Pradesh meets all its electricity demand for green hydrogen production with renewables that are co-located with electrolyzers within the state, and excess generation from these renewables is exported to the grid. This scenario, which does not assume that long-duration electricity or hydrogen storage will also be co-located with electrolyzers, was used as a test case to determine whether co-location of renewables is feasible to meet Uttar Pradesh's entire anticipated green hydrogen demand. The cumulative undiscounted system cost from 2023–2050 for this scenario is approximately 82% higher than the first green hydrogen scenario, although the results do not capture the procurement cost for out-of-state power, which will be higher in scenarios with more imports, or potential subsidies for green hydrogen projects. However, the extremely rapid and large buildout of wind that occurs in the RE Policy, Baseline Green H_2, Co-Located RE scenario was not considered feasible by stakeholders in Uttar Pradesh. The approach that Uttar Pradesh ultimately takes for meeting its green hydrogen goals could fall within these two scenarios, incorporating some combination of imports and co-located renewables, along with, potentially, long-duration electricity and/or hydrogen storage, based on the trade-offs outlined in this analysis and other state priorities (Figure ES-5).

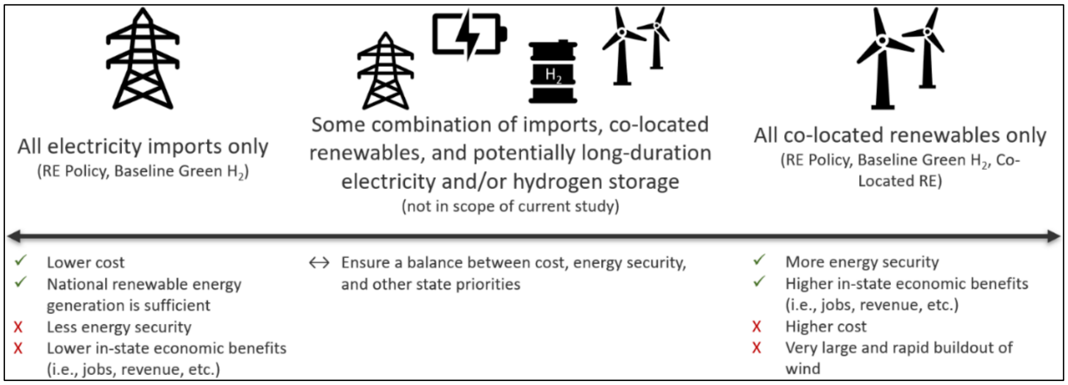

Figure ES-5. Spectrum of potential approaches to meet Uttar Pradesh's green hydrogen targets

Uttar Pradesh can cost-effectively and reliably achieve a low-carbon power sector by 2050.

The model results, which seek to minimize total system costs while meeting various physical and policy constraints, show that Uttar Pradesh can achieve a highly decarbonized electricity grid by mid-century, including in scenarios with a high reliance on imports. This is because there exists sufficient excess renewable energy generation in India as a whole, presenting Uttar Pradesh with significant opportunities to procure out-of-state renewables in addition to in-state clean energy resources. By 2050, the study finds that Uttar Pradesh could meet between 92% (in the RE Policy scenario) and 94% (in the RE Policy, Baseline Green H_2 scenario) of its annual demand with non-fossil fuel resources, assuming that any electricity imports would be met by out-of-state clean energy generators.

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1 Introduction

In support of India's national decarbonization targets, the Government of Uttar Pradesh aims to increase renewable energy capacity through multiple means by 2030. The *Uttar Pradesh Solar Energy Policy* sets a goal of 22 GW of solar photovoltaic (PV) capacity by 2027 (UPNEDA 2022). The government also plans to develop 12 GW of in-state pumped hydropower capacity by 2028. Additionally, the *Uttar Pradesh Green Hydrogen Policy 2024* details a strategy to make Uttar Pradesh a leading producer of green hydrogen and green ammonia globally, setting production targets and outlining incentives (JMK Research & Analytics 2024).[4]

To support the Government of Uttar Pradesh in this transition, and to help inform state policymakers, regulators, planners, and system operators, the National Renewable Energy Laboratory (NREL) undertook a long-term capacity expansion planning study in partnership with RMI and the Uttar Pradesh New and Renewable Energy Development Agency (UPNEDA). This study uses NREL's flagship capacity expansion planning tool for the power sector, the Regional Energy Deployment System-India (ReEDS-India) model, to understand the generation and transmission needs of Uttar Pradesh, considering the aforementioned targets and looking beyond to 2050.

The study used scenario analysis to assess a range of potential future outcomes and to identify least-cost options and opportunities for Uttar Pradesh's power system. The results convey the potential impact of Uttar Pradesh's state-level policies on power sector development throughout India because ReEDS-India is a national-level model that is adapted in this study to focus on Uttar Pradesh in greater detail. This model feature can yield important insights because Uttar Pradesh, as the most populous state in India with the second-highest annual demand for electricity after Maharashtra, can have a significant influence on the country's ability to reach its national energy transition goals.[5]

Section 2 provides a brief overview of the modeling approach, data inputs, key assumptions, and scenarios assessed for this study. Section 3 shares the results and insights from the Reference scenario. Sections 4 and 5 focus on scenarios related to policy targets and electricity demand for green hydrogen production, respectively. Finally, Section 6 concludes the report with key near-term and long-term takeaways, along with a discussion of the study's limitations and potential next steps. The outputs of this study are also used in an accompanying air quality analysis to assess the pollution and health impacts of the various long-term planning trajectories (Ravi et al., 2024).

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[4] The modeling for this study is primarily based on UPNEDA's draft green hydrogen policy, released in 2023 (UPNEDA 2023). In March 2024, the Uttar Pradesh state government officially approved the policy, which has some differences compared to the 2023 draft (JMK Research & Analytics 2024). However, these policy modifications do not result in significant changes to the key model results and takeaways (see Appendix A.2 for more information).

[5] In 2022, Uttar Pradesh accounted for approximately 9.4% of national electricity demand in India (CEA 2022).

2 Modeling Framework and Key Assumptions

The primary tool used in this study is NREL's 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. Importantly, NREL's modeling framework includes co-optimized decisions about generation, energy storage, transmission, and reserves investments needed to meet future demand while maintaining reliable electricity supply across daily, seasonal, and yearly timescales; this is a key part of planning for increased deployment of wind and solar generation, because both technologies are subject to variable weather. The outputs of the ReEDS-India model include projections of generation capacity additions, generation retirements, and additional transmission capacity along different corridors, as well as generation fleet operations, transmission flows, and reserves requirements.

This section provides details on the input assumptions in the ReEDS-India model for Uttar Pradesh. For details on model inputs for the rest of India, see Rose et al. (2020) and Chernyakhovskiy et al. (2021). Additional information about ReEDS can be found in Ho et al. (2021). A publicly available version of the ReEDS model developed for national-level planning in India can be accessed from https://www.nrel.gov/analysis/reeds/.

2.1 Model Regions

The national ReEDS-India model represents each Indian state and union territory as one balancing area within India's transmission network. However, because Uttar Pradesh is the focus of this study, each of the five distribution companies (DISCOMs) in the state is modeled in detail and assumed to operate as a separate balancing area (Figure 1).

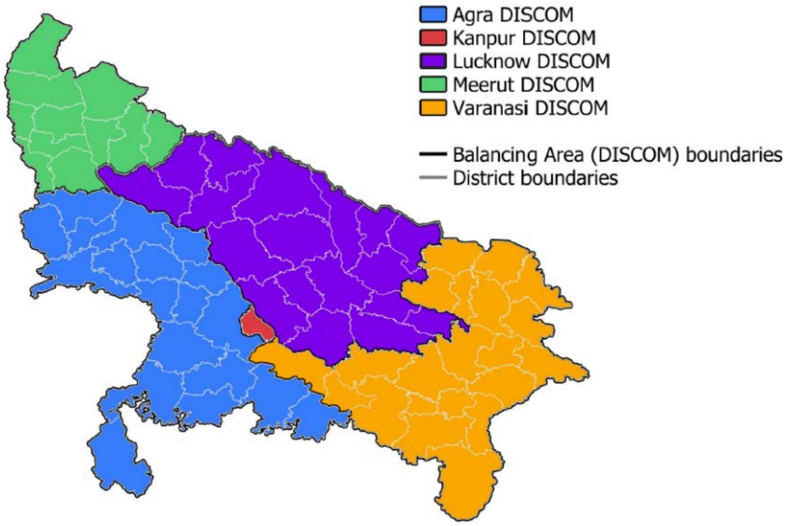

Figure 1. Uttar Pradesh balancing areas

Electricity demand, transmission lines, and non-variable renewable energy generators are aggregated for each balancing area. This study does not distinguish between the ownership of assets within a balancing area. All private, state, and central government-owned power system assets, including transmission lines, substations, and generators, are aggregated based on their geographic location within the boundaries of each balancing area. Renewable energy resource regions for Uttar Pradesh, which are designed to capture differences in wind and solar resources at a higher level of spatial granularity, were developed based on windspeed data (Figure 2) and global horizontal irradiance data (Figure 3) for the state. Uttar Pradesh was divided into 21 resource regions, one for the Kanpur DISCOM due to its smaller size and five each for the remaining four larger DISCOMs (Agra, Kanpur, Meerut, and Varanasi). Within the four larger DISCOMs, the five resource regions were created using a clustering algorithm that grouped together relatively similar wind and solar resources to capture the variation in renewable energy quality within a balancing area more precisely. These resource regions are shown in Figure 4.

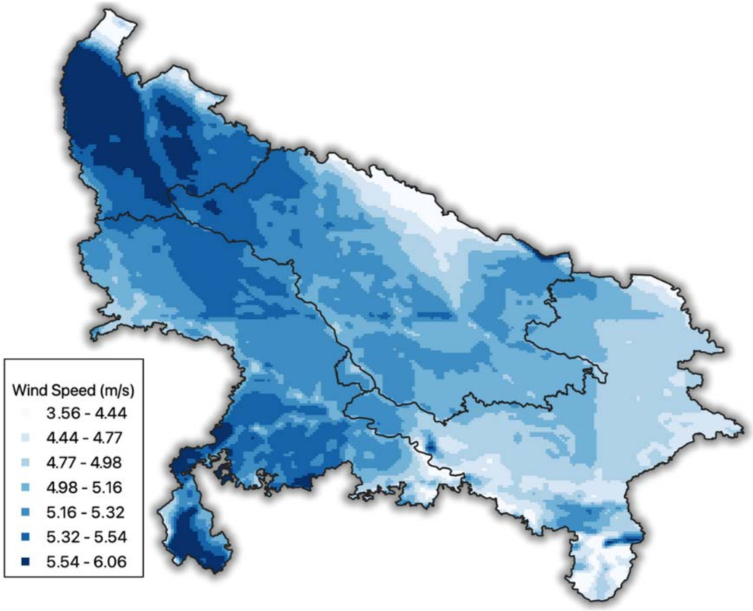

Figure 2. Uttar Pradesh wind speed data (80 m hub height)

Source: Weather Research and Forecasting Model.

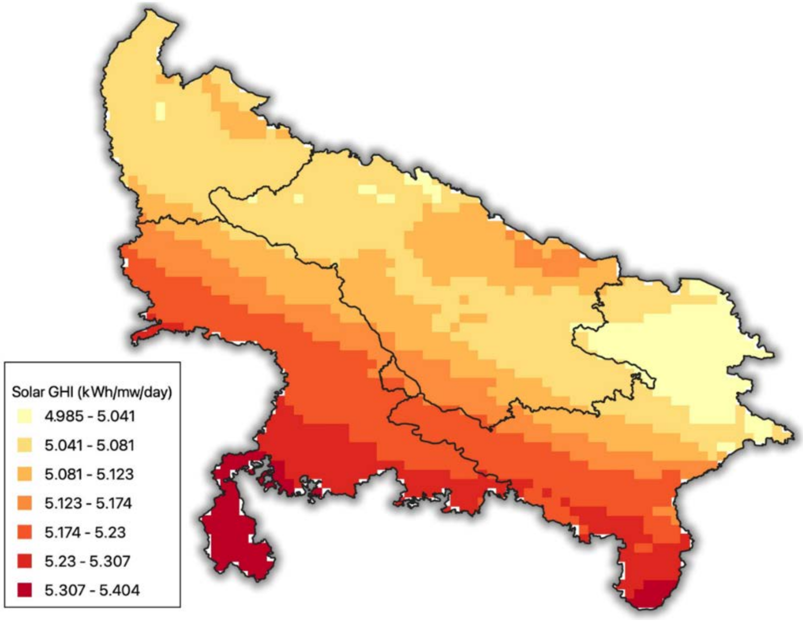

Figure 3. Uttar Pradesh global horizontal irradiance data

Source: Physical Solar Model.

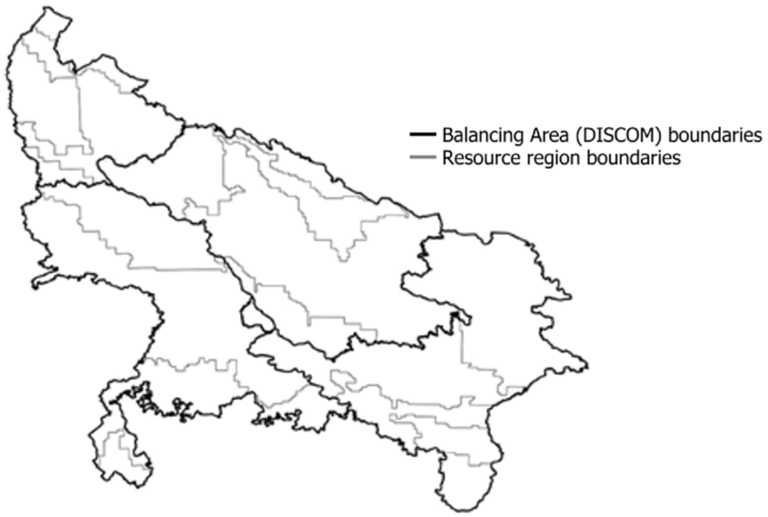

Figure 4. Uttar Pradesh resource regions

2.2 Demand Projections

The electricity demand projections are based on the 20th Electric Power Survey published by the Central Electricity Authority (CEA) (CEA 2022). The approach used to forecast peak demand and total electricity consumption through 2050 for each balancing area is described in Chernyakhovskiy et al. (2021). The projected growth in peak demand and annual energy consumption for each balancing area in Uttar Pradesh is summarized in Table 1. The variability of electricity demand within a particular year is represented with 35 chronological time slices, or representative hour groupings. These time slices are designed to capture changes in seasonal and daily demand patterns, as well as wind and solar resource availability. The time slices include five seasons (winter, spring, summer, rainy, and autumn) with seven representative times of day per season (night, sunrise, morning, afternoon, sunset, evening, and peak).[6] For more information on the design of the time slices, see Rose et al. (2020).

Table 1. Projected Growth in Uttar Pradesh Electricity Demand, 2020–2050

	Annual Energy Consumption (TWh)				Peak Demand (GW)			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Agra DISCOM	31.9	45.8	70.0	91.3	4.4	8.6	11.2	15.0
Kanpur DISCOM	4.2	5.5	6.8	7.1	0.6	0.8	0.9	1.0
Lucknow DISCOM	29.5	47.2	82.5	117.0	4.0	8.8	12.7	18.2
Meerut DISCOM	41.7	68.2	117.9	166.8	5.7	11.9	16.2	22.8
Varanasi DISCOM	34.0	51.6	83.3	111.9	4.7	7.3	11.3	15.2
Uttar Pradesh Total	141.4	218.3	360.5	494.1	19.4	37.4	52.3	72.2

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[6] The seasons comprise of the following months: winter (December and January), spring (February and March), summer (April, May, and June), rainy (July, August, and September), and autumn (October and November).

2.3 Technology Costs

Initial capital and operational costs for generation technologies are based on NREL's 2022 Annual Technology Baseline (NREL 2022), with adjustments based on labor costs in India. Figure 5 shows the capital cost assumptions and trajectories for key technologies in this study. Detailed inputs and assumptions about technology performance characteristics, including operational and maintenance costs, fuel prices, operating constraints, as well as renewable energy resource availability and renewable energy supply curves, are available in Rose et al. (2020). Electricity imports from Nepal, generated by hydropower, are also a resource option in the ReEDS-India model that can serve demand in Uttar Pradesh. Further details on the assumptions for Nepal imports can be found in Appendix A.3.

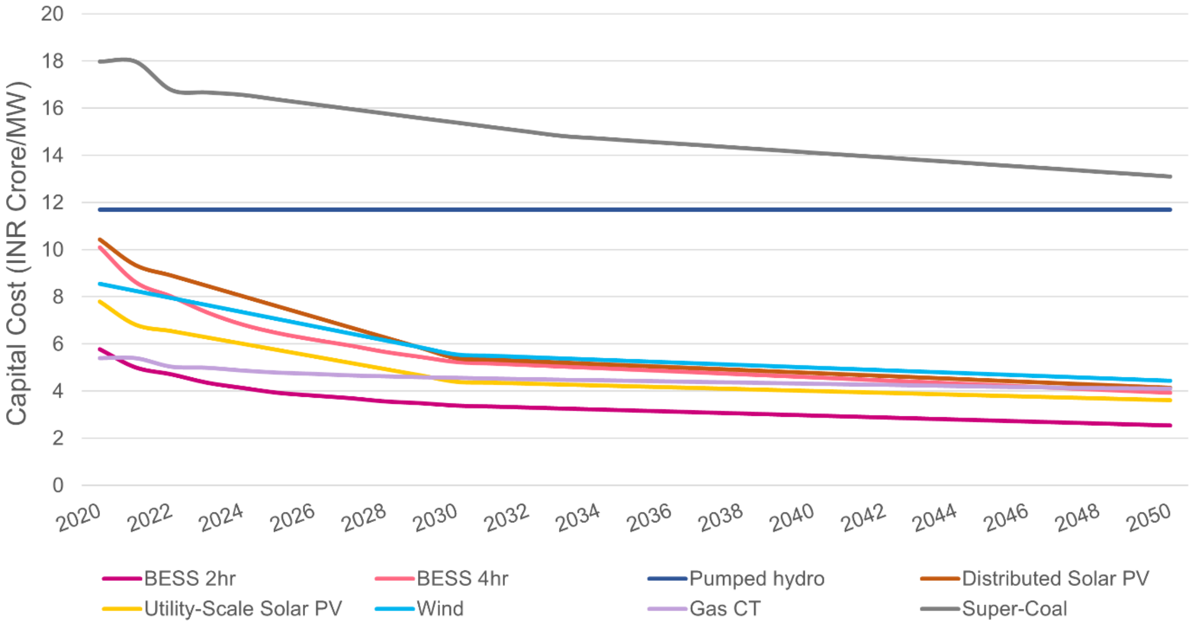

Figure 5. Capital cost assumptions for select key technologies (2020–2050)

Note: CT = combustion turbine, Super-Coal = supercritical coal, INR = Indian rupee, Crore = 10 million Indian rupees. The values are nominal costs with 2020 as the base year.

2.4 Study Scenarios

The four scenarios considered in this study are summarized in Table 2. The Reference scenario represents a business-as-usual case, in which no additional renewable energy policy targets are met and there is no green hydrogen generated in Uttar Pradesh, and thus no additional electricity demand, above what is already embedded into the CEA's 20th Electric Power Survey forecast (see Appendix A.2 for more information). The Renewable Energy (RE) Policy scenario uses the same demand projections as the Reference scenario and accounts for UPNEDA's pumped storage hydropower (12 GW by 2028) and solar PV (22 GW by 2027) policies and targets. Details about the Reference and RE Policy scenarios can be found in Sections 3 and 4, respectively.

The next two scenarios, RE Policy, Baseline Green Hydrogen (H_2) and RE Policy, Baseline Green H_2, Co-Located RE, include the renewable energy policy targets and also account for UPNEDA's green hydrogen policy by converting production targets, which are extrapolated out to 2030 and 2050 (1.1 MMT by 2030 and 2.3 MMT by 2050), into an increase in electricity demand (53 TWh by 2030 and 110 TWh by 2050). The difference between these two scenarios is how the electricity needed to produce green hydrogen is generated. In the RE Policy, Baseline Green H_2 scenario, the electricity to produce green hydrogen can be generated by in-state or out-of-state renewables and is supplied by the national grid. In the RE Policy, Baseline Green H_2, Co-Located RE scenario, the electricity to produce green hydrogen can only be met by in-state co-located renewables (i.e., renewables that are located within same balancing area as the electrolyzers that produce the hydrogen). This second green hydrogen scenario was developed to test whether such a co-location strategy would be feasible for Uttar Pradesh, and does not account for the potential of long-duration electricity or hydrogen storage to also be co-located with the electrolyzers. For both green hydrogen scenarios, the ReEDS-India model is only representing the impact of hydrogen production on electricity demand and is not optimizing investments in hydrogen production technologies or representing hydrogen as a supply-side fuel for electricity generation. Further details on these scenarios, including how the green hydrogen goals are converted into electricity demand and incorporated into the ReEDS-India model, can be found in Section 5 and Appendix A.2.

All scenarios reflect the CEA's revised power sector reliability requirement that states maintain a 7% planning reserve margin, as well as India's national target of achieving 50% of its installed power capacity from non-fossil fuel resources by 2030. Furthermore, the default assumption for all scenarios is that no new gas-fired power plants will be built in Uttar Pradesh, reflecting informed stakeholder input about the feasibility of developing the supporting pipeline infrastructure. Finally, the models were run from 2023 to 2050.

Table 2. Description of Study Scenarios

Scenario Name	Renewable Energy Policy Targets	Green Hydrogen Production	Electricity for Green Hydrogen Production
Reference	None	None	N/A
RE Policy	UPNEDA policies: pumped hydro (12 GW by 2028) and solar PV (22 GW by 2027) targets		
RE Policy, Baseline Green H_2		Baseline growth in green hydrogen production (1.1 MMT and 53 TWh by 2030, 2.3 MMT and 110 TWh by 2050)	Electricity for green hydrogen production can be provided by in-state or out-of-state renewables
RE Policy, Baseline Green H_2, Co-Located RE[7]			Electricity for green hydrogen production can only be met by in-state co-located (i.e., in the same balancing area) renewables

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[7] This scenario was developed as a test case to determine the feasibility of using co-located renewables, without co-located long-duration electricity and/or hydrogen storage, to meet all of Uttar Pradesh's projected green hydrogen production needs.

3 Reference Scenario Results

Based on available data, the ReEDS model assumes that 2.3 GW of solar PV exists in Uttar Pradesh by the end of 2022 (MNRE 2022). The Reference scenario represents a business-as-usual case, assuming that no additional renewable energy targets are prescribed in the model and that no additional green hydrogen will be produced in the state beyond what is already assumed by the CEA's 20th Electric Power Survey. More details on the CEA's assumptions can be found in Appendix A.2.

3.1 Capacity

In the Reference scenario, coal capacity remains mostly steady in the mid-2020s, and declines by 49% from 2030–2050 due to a combination of coal power plants reaching the end of their lifetime and economic retirements. Wind capacity significantly increases starting in the 2030s (when the capital cost drops to 6 INR Crore/MW or lower), battery energy storage systems (BESS) increase starting in the late 2030s and early 2040s (when the capital cost drops to 5 INR Crore/MW or lower), and solar PV is added in the late 2040s (when the capital cost drops to 4 INR Crore/MW or lower). The rise in 4-hour BESS capacity coincides with the rise in variable renewable energy such as wind and solar PV. These trends are shown in Figure 6 and broken down by balancing area in Figure 7. The wind capacity is almost exclusively added to the Meerut DISCOM, owing to its higher average wind speeds (Figure 2). As a result, total power capacity in Uttar Pradesh shifts to being predominantly located in the Meerut DISCOM. BESS capacity is built primarily in the Agra DISCOM, while economic additions of solar PV occur in the Varanasi DISCOM. Total in-state capacity, which is 25 GW in 2030, rises to 112 GW in 2050.

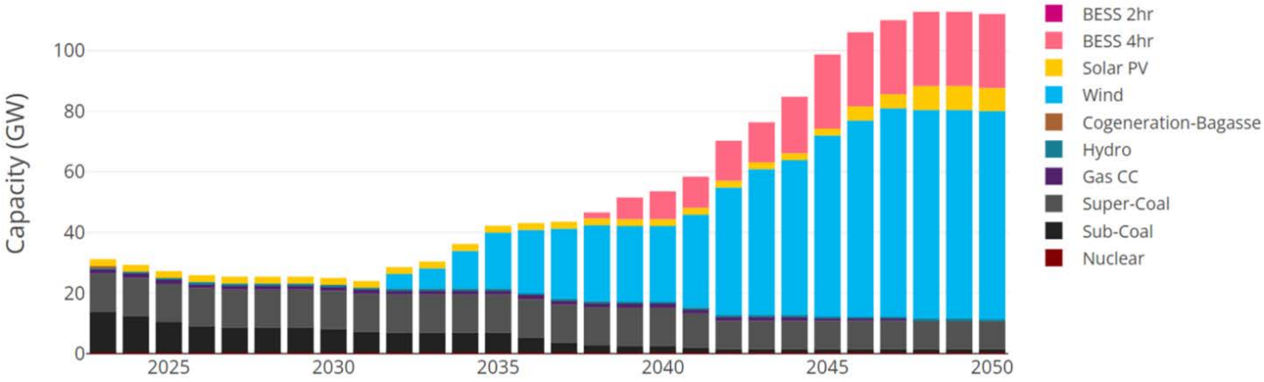

Figure 6. Reference scenario: Uttar Pradesh installed capacity (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

Text Box 1. Uttar Pradesh has not traditionally been considered a state with significant wind potential, so why is the model building large amounts of wind?

Many previous assessments of wind resources in Uttar Pradesh, as well as input from stakeholders, indicate that wind potential in the state could be lower than what is shown in this model result. This difference could be attributed to **varying assumptions regarding costs, what wind speeds and capacity factors are feasible for wind development, and land availability**.

For example, the 2016 *Re-assessment of India's On-shore Wind Power Potential* report uses one data set with a minimum wind speed cutoff of 5 meters per second (m/s), and another with a cutoff of 6 m/s (CSTEP, WFMS, and SSEF 2016). Another study by India's National Institute of Wind Energy, based on a hub height of 150 m, uses a minimum wind capacity factor cutoff of 25% when assessing the potential for wind energy in Uttar Pradesh (NIWE 2023). **The dataset used in this ReEDS-India model does not set a minimum wind speed or capacity factor cutoff**, based on the assumption that, **as wind technology prices are projected to decline over time (Figure 5), building resources in regions with relatively lower wind speeds could become cost-effective** and thereby more attractive for future development.

Wind capacity starts to be built in Uttar Pradesh roughly when the capital cost dips below 6 INR Crore/MW; this is when the wind speeds of 5–6 m/s in the Meerut DISCOM (Figure 2), with an average capacity factor of around 20%, start to be developed in the model. These wind resources, which are not commercially viable today, are thus not captured in many present-day assessments but are potentially relevant in this forward-looking assessment. Furthermore, **India's high-wind states (i.e., Andhra Pradesh, Gujarat, Karnataka Maharashtra, Rajasthan, and Tamil Nadu) are expected to develop a large portion of the country's highest-quality wind resources by the mid-2030s**. At this later phase of India's wind development, the wind resources in Uttar Pradesh become more competitive.

Finally, there could be **different assumptions between this study and others regarding the availability and cost of land** for wind development in the state. For instance, the NIWE 2023 assessment places restrictions on agricultural land that can be developed for wind energy in Uttar Pradesh (i.e., 30% of potential cultivable land is available for wind development). This study, however, assumes that wind can be developed on agricultural land (i.e., land referred to as different categories of "cropland" in the European Space Agency GlobCover global land use dataset used for the analysis).

A more recent analysis of onshore wind technical potential in India finds that, at a minimum onshore wind speed threshold of 5 m/s, there is approximately 154 GW and 266 GW of technical potential in Uttar Pradesh at hub heights of 150 m and 200 m, respectively (von Krauland and Jacobson 2024). The ReEDS model results for wind build-out in Uttar Pradesh, for all scenarios except when co-located renewables meet all of the state's anticipated demand for green hydrogen by 2050 with no storage or hydrogen production flexibility, fall well within these thresholds.

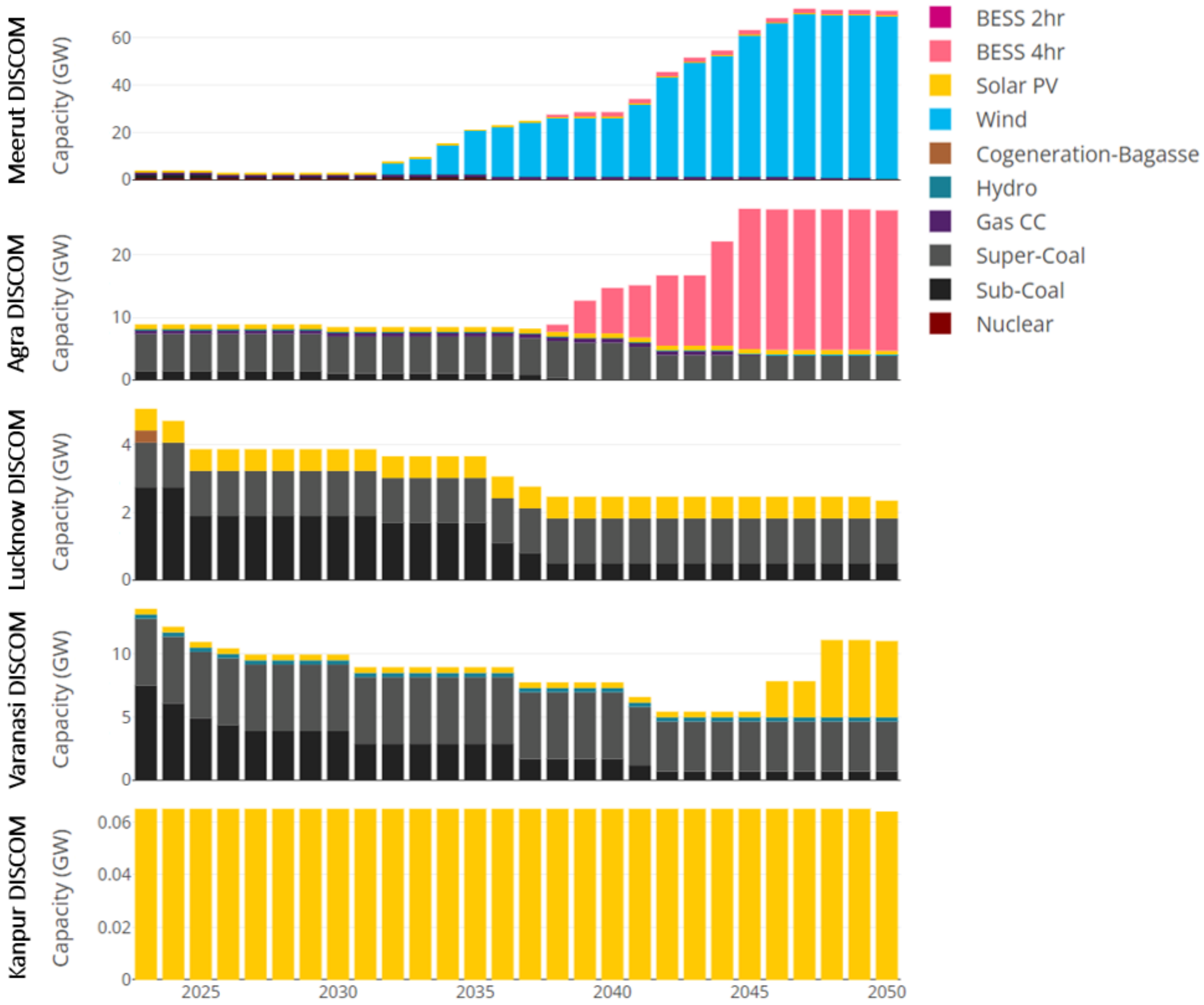

Figure 7. Reference scenario: Uttar Pradesh installed capacity by balancing area (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. Y-axis scales are different.

3.2 Generation

In the Reference scenario, Uttar Pradesh increasingly relies on electricity imports, primarily from within India, to meet annual demand (Figure 8). The model results show that the state imports almost 184 TWh of electricity (84% of annual demand) in 2030, which rises to 303 TWh (61% of annual demand) by 2050. In addition to imports from neighboring states within India, these numbers also account for hydropower imports from Nepal. In-state renewables, primarily wind, serve 30% of Uttar Pradesh's annual electricity demand in 2050.

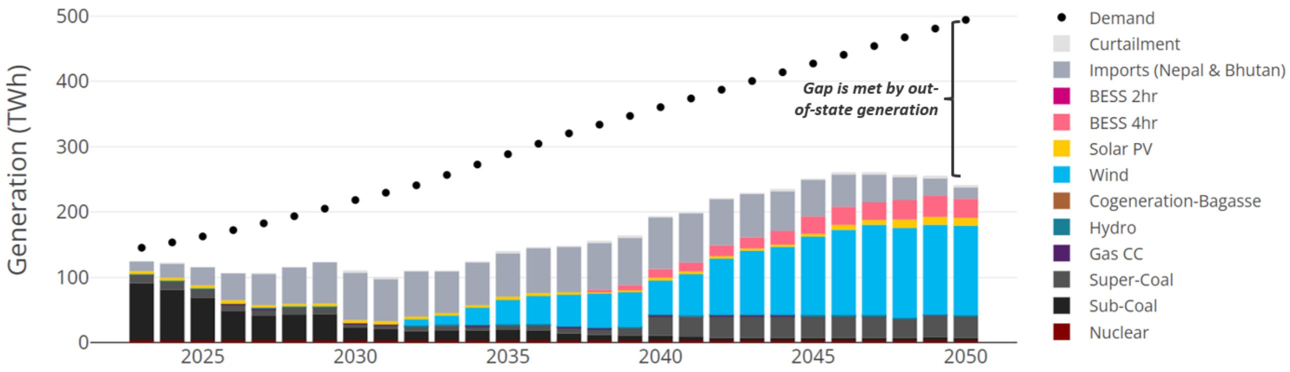

Figure 8. Reference scenario: Uttar Pradesh annual generation and demand (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

Results point to the evolving role of coal in Uttar Pradesh. In 2025, Uttar Pradesh relies significantly on coal capacity and imports throughout all seasons and time slices. In 2030, coal instead provides seasonal flexibility and primarily generates power in winter, spring, and autumn (Figure 9). Thus, even though coal capacity only decreases by 10% from 2025–2030 (22.6 GW to 20.3 GW) because certain power plants reach the end of their lifetime, generation decreases by 67% (78.3 TWh to 26.1 TWh). In 2050, the dispatch pattern of coal is similar to 2030, and a share of imports is replaced by substantial wind power generation across all seasons and time slices (Figure 10). Uttar Pradesh relies most heavily on imports during the summer and rainy seasons, when demand is highest, and BESS during the evening and national peak time slices. Curtailment is not significant in the Reference scenario, as the percentage of annual variable renewable energy generation that is curtailed is 0.5% and 1% in 2030 and 2050, respectively.

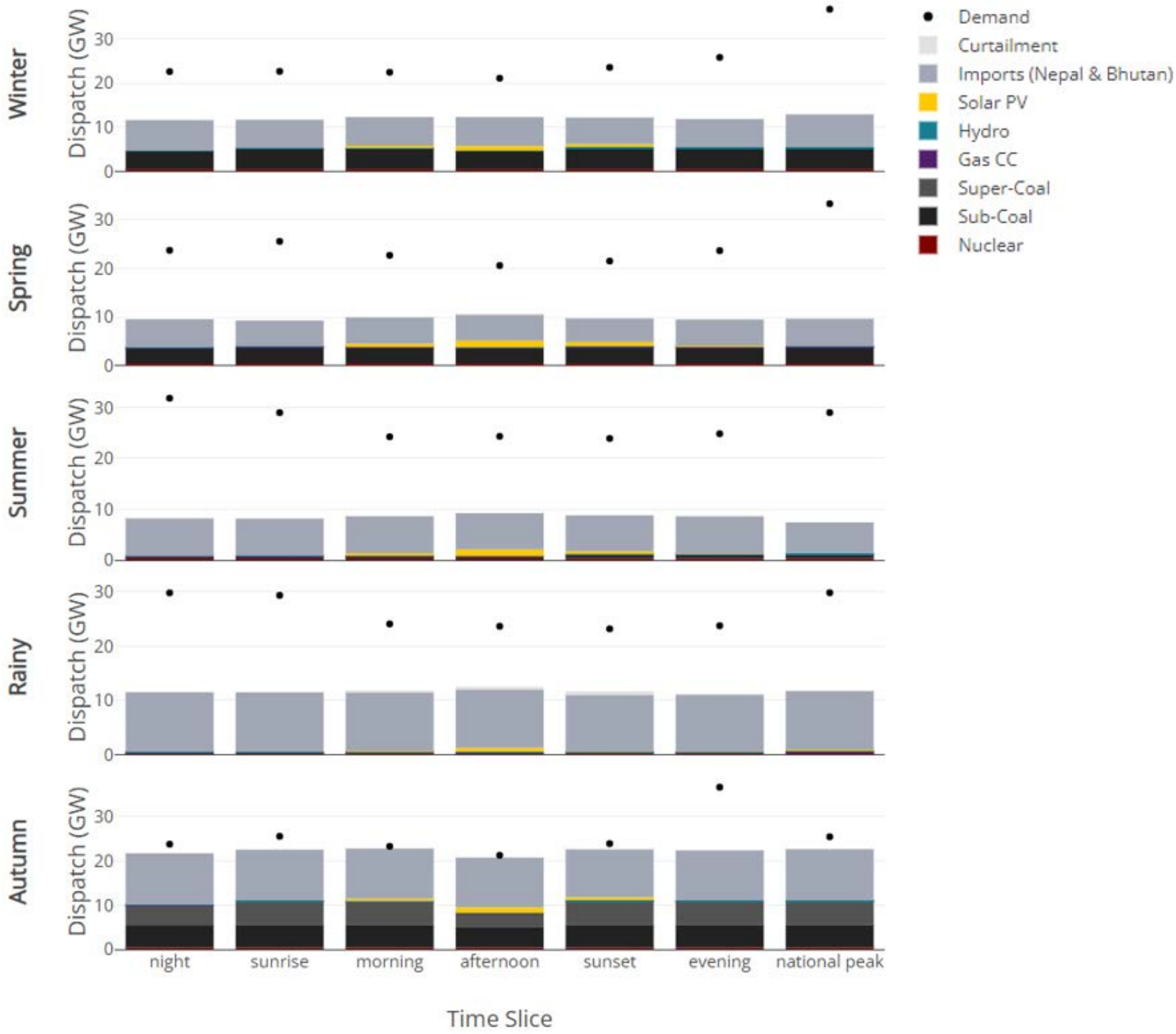

Figure 9. Reference scenario: Uttar Pradesh generation and demand by time slice (2030)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

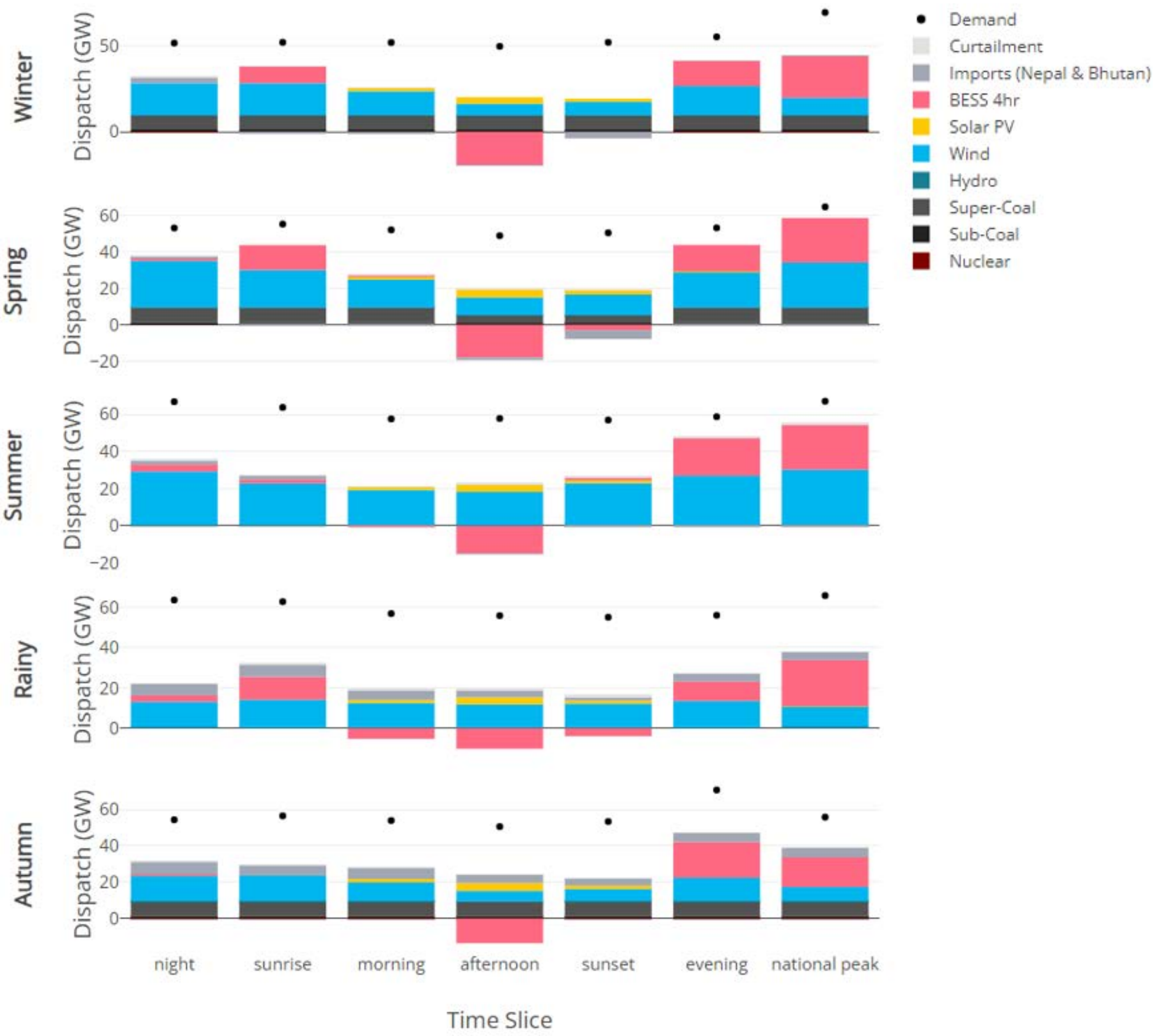

Figure 10. Reference scenario: Uttar Pradesh generation and demand by time slice (2050)

Note: Super-Coal = supercritical coal, Sub-Coal = subcritical coal. The negative dispatch values refer to charging storage technologies (i.e., BESS, pumped hydro, etc.) or electricity exports. Y-axis scales are different.

3.3 Transmission

In the Reference scenario, no new transmission investments occur between Uttar Pradesh and neighboring states or within Uttar Pradesh by 2030. From 2030–2050, however, new transmission is built between the Agra DISCOM and Rajasthan (29.3 GW), the Lucknow DISCOM and Rajasthan (2.0 GW), and the Varanasi DISCOM and Rajasthan (1.2 GW). This result, displayed in Figure 11, indicates that Uttar Pradesh is relying heavily on lower-cost generation from Rajasthan to meet its demand.

Figure 11. Reference scenario: Cumulative transmission investment (2030–2050)

3.4 System Costs

System costs are reported in six categories: capacity, fixed operations and maintenance (O&M), fuel, operating reserves, substations, transmission, and variable O&M. These are the cumulative undiscounted system costs for all of Uttar Pradesh; it is important, however, to note that the model minimizes costs across all of India. For all scenarios, the national cost differences are negligible, varying only within approximately 1% from the Reference scenario. The state-level costs do not capture the power procurement cost or any future transmission fees for out-of-state power, which will be higher in the scenarios with more imports. A percentage breakdown of the system costs by category for the Reference scenario is shown in Figure 12.

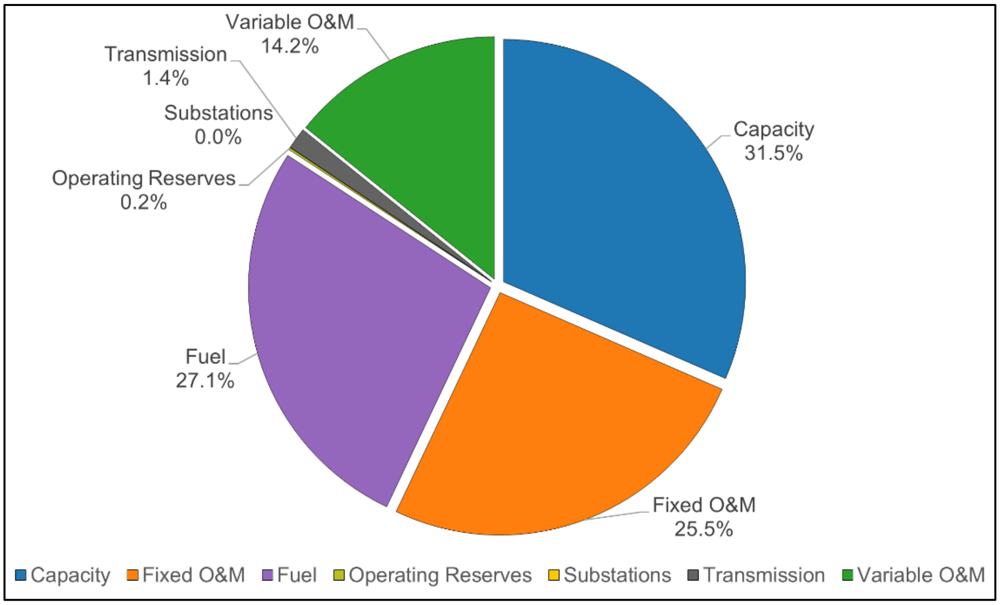

Figure 12. Reference scenario: Percentage breakdown in Uttar Pradesh system costs by category (2023–2050)

4 RE Policy Scenario Results

The RE Policy scenario contains the same assumptions as the Reference scenario, with the additions of UPNEDA's policies and targets for pumped hydro and solar PV. The purpose of this scenario is to examine the impacts of state-level renewable energy policies and targets on the long-term development of the power sector, particularly in comparison to the Reference scenario, on key metrics such as clean energy capacity and generation, reliance on imports, energy storage deployment, and transmission investments.

Consultations with UPNEDA indicated ongoing plans to develop 12 GW of pumped hydro capacity in the state by 2028, including a 3.66-GW plant under construction in the Sonbhadra district scheduled to begin operation by the end of 2024. In addition to the Sonbhadra district, other districts targeted for pumped hydro development are Prayagraj, Chandauli, and Mirzapur, all of which are in the Varanasi DISCOM territory. Therefore, these plans were included in the model via pumped hydro prescriptions in the Varanasi DISCOM of the following amounts: 3.66 GW in 2024 and 2.085 GW annually from 2025 to 2028, reaching 12 GW total by the end of 2028.

UPNEDA's solar PV policy was also translated into annual capacity prescriptions (UPNEDA 2022). The policy targets amount to 22 GW of solar PV by 2027 with the following breakdown: 14 GW of utility-scale solar PV, 4.5 GW of residential rooftop solar PV, 1.5 GW of non-residential rooftop solar PV, and 2 GW of other distributed solar PV. The Reference scenario already includes 2.3 GW of existing solar PV (1.8 GW utility-scale and 0.4 GW distributed) in Uttar Pradesh at the end of 2022 (Section 3). Thus, in the RE Policy scenario, the model includes prescriptions of approximately 2.4 GW of utility-scale PV and approximately 1.5 GW of distributed PV annually from 2023 to 2027, resulting in a total of 14 GW of utility-scale PV and 8 GW of distributed PV by the end of 2027, in accordance with UPNEDA's policy. Appendix A.1 contains additional details on how these state-level policy targets were assigned to balancing areas within Uttar Pradesh.

4.1 Capacity

In the RE Policy scenario, coal and wind capacity are unchanged compared to the Reference scenario. The growth in pumped hydro is entirely attributable to UPNEDA's target, as no additional capacity is added beyond the 12 GW in place by 2028 and no capacity is added throughout the entire time horizon of the Reference scenario. Similarly, the growth in solar PV capacity is almost entirely attributable to UPNEDA policies, as only 2.8 GW of capacity is added by 2050 beyond the 22 GW in place by 2027. Another near-term implication of the Uttar Pradesh pumped hydro and solar PV targets is the installment of 1.5 GW of 2-hour BESS in the state by 2030, which does not occur in the Reference scenario. This capacity is replaced by growth in 4-hour BESS, culminating in 24.7 GW of 4-hour BESS capacity in 2050. The capacity of 4-hour BESS in 2050 is only 0.3 GW higher in the RE Policy scenario compared to the Reference scenario. These results are summarized in Figure 13 for the entire state and in Figure 14 based on balancing area, while Figure 15 shows a difference plot comparing installed capacity in Uttar Pradesh in the RE Policy scenario to the Reference scenario. Total in-state capacity, which is 25 GW in 2030, rises to 112 GW in 2050.

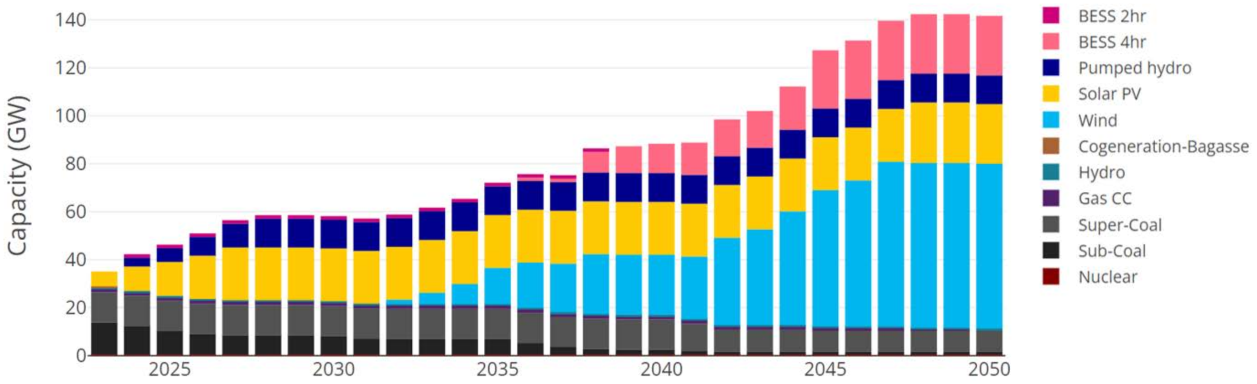

Figure 13. RE Policy scenario: Uttar Pradesh installed capacity (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

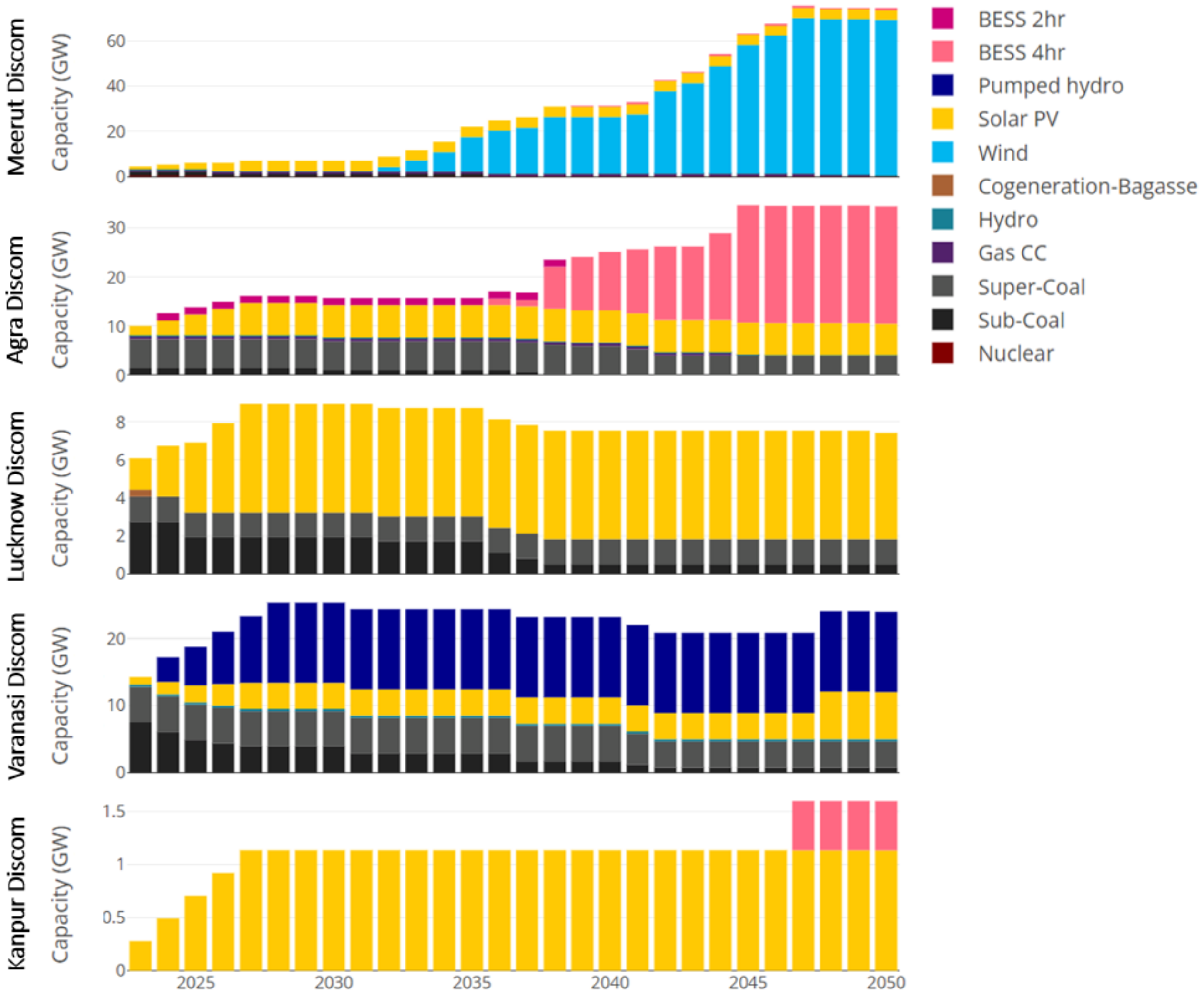

Figure 14. RE Policy scenario: Uttar Pradesh installed capacity by balancing area (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. Y-axis scales are different.

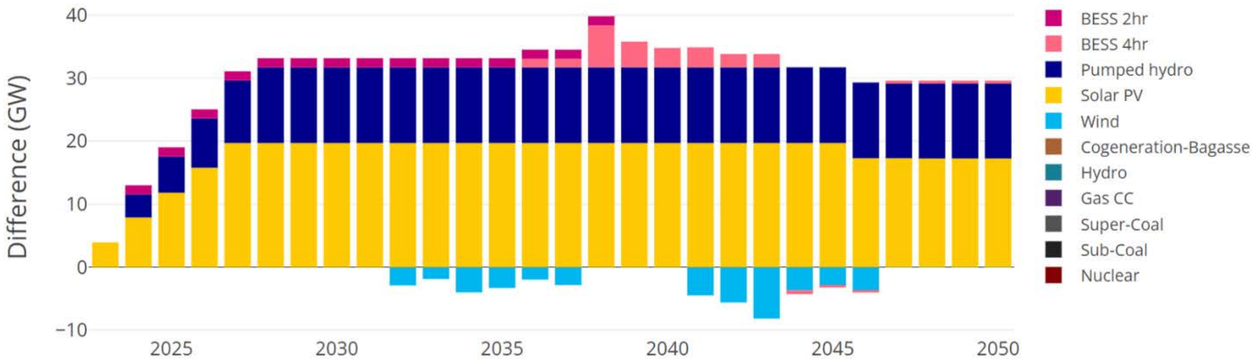

Figure 15. RE Policy scenario: Difference in installed capacity in Uttar Pradesh compared to the Reference scenario (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

4.2 Generation

In the RE Policy scenario, Uttar Pradesh's reliance on imports, while still substantial, is lower than in the Reference scenario. The state imports 152 TWh of electricity (70% of annual demand) in 2030, which rises to 278 TWh (56% of annual demand) in 2050 (Figure 16). In comparison, imports are 184 TWh (84% of annual demand) and 303 TWh (61% of annual demand) in 2030 and 2050, respectively, in the Reference scenario. In-state renewables, primarily wind, serve 36% of Uttar Pradesh's annual electricity demand in 2050, up from 30% in the Reference scenario. Figure 17 shows a difference plot comparing generation in Uttar Pradesh in the RE Policy scenario to the Reference scenario. The 2030 (Figure 18) and 2050 (Figure 19) dispatch plots shed light on the diurnal and seasonal dispatch of the technologies featured in the RE Policy scenario, namely solar PV and pumped hydro. Compared to the Reference scenario, the generation patterns of coal, wind, and BESS are similar. As expected, solar PV generation is highest in the afternoon. Curtailment, which is 1.5% of variable renewable energy generation in 2030 and 2% in 2050, is associated with periods of solar generation. Charging of storage technologies, both pumped hydro and BESS, also occurs during periods of solar generation. Pumped hydro generates in all seasons, and predominantly in the evening and national peak time slices.

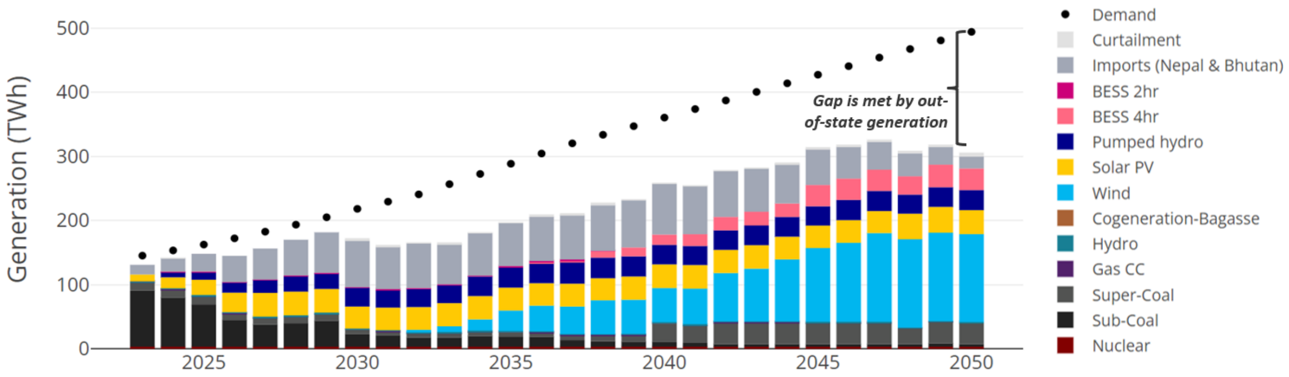

Figure 16. RE Policy scenario: Uttar Pradesh annual generation and demand (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

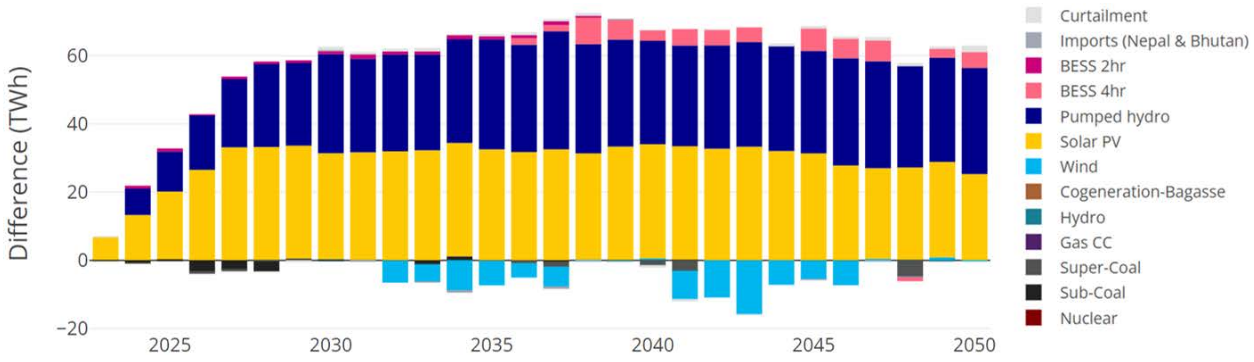

Figure 17. RE Policy scenario: Difference in generation in Uttar Pradesh compared to the Reference scenario (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

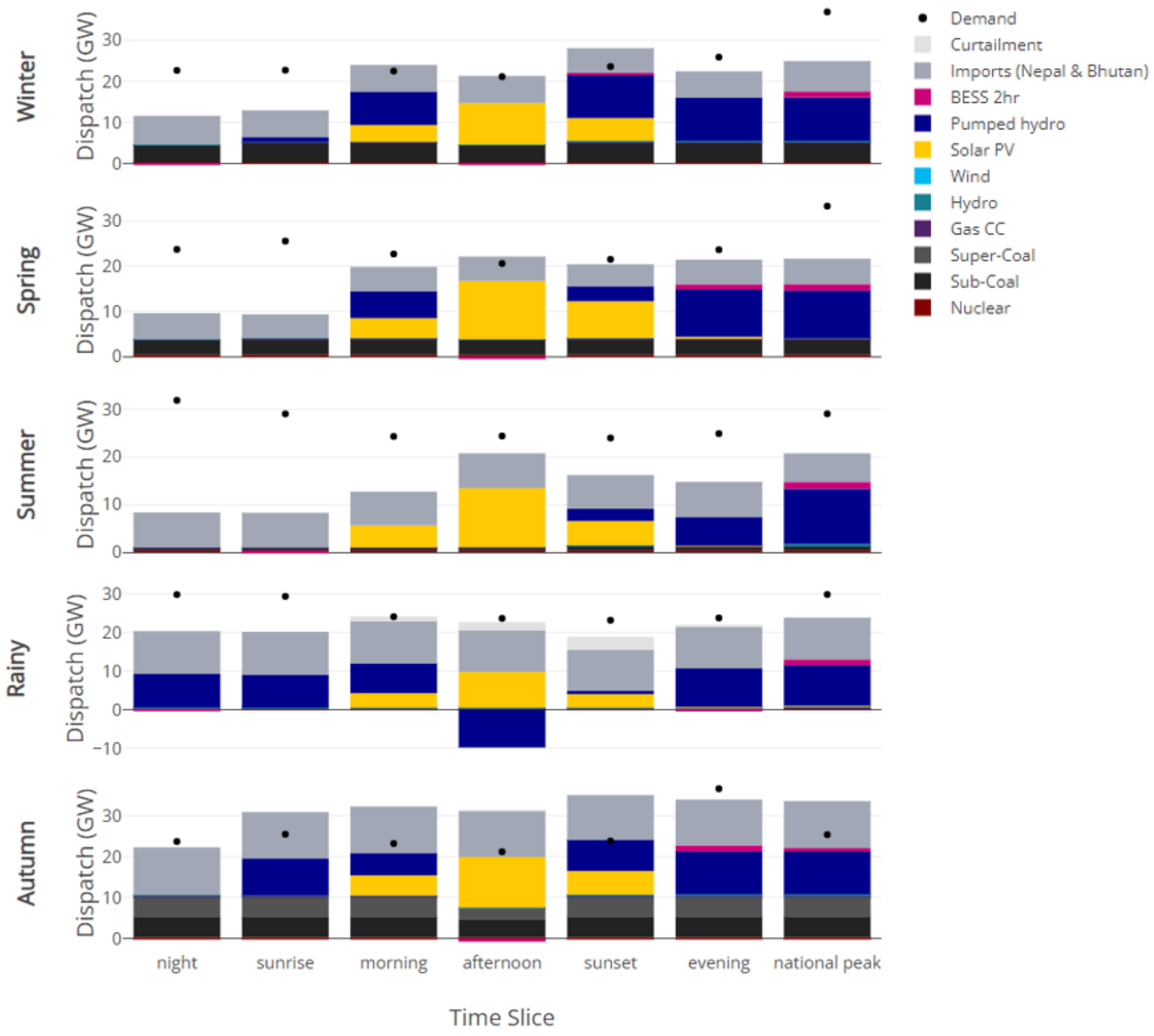

Figure 18. RE Policy scenario: Uttar Pradesh generation and demand by time slice (2030)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. The negative dispatch values refer to charging of storage technologies (i.e., BESS, pumped hydro, etc.) or electricity exports.

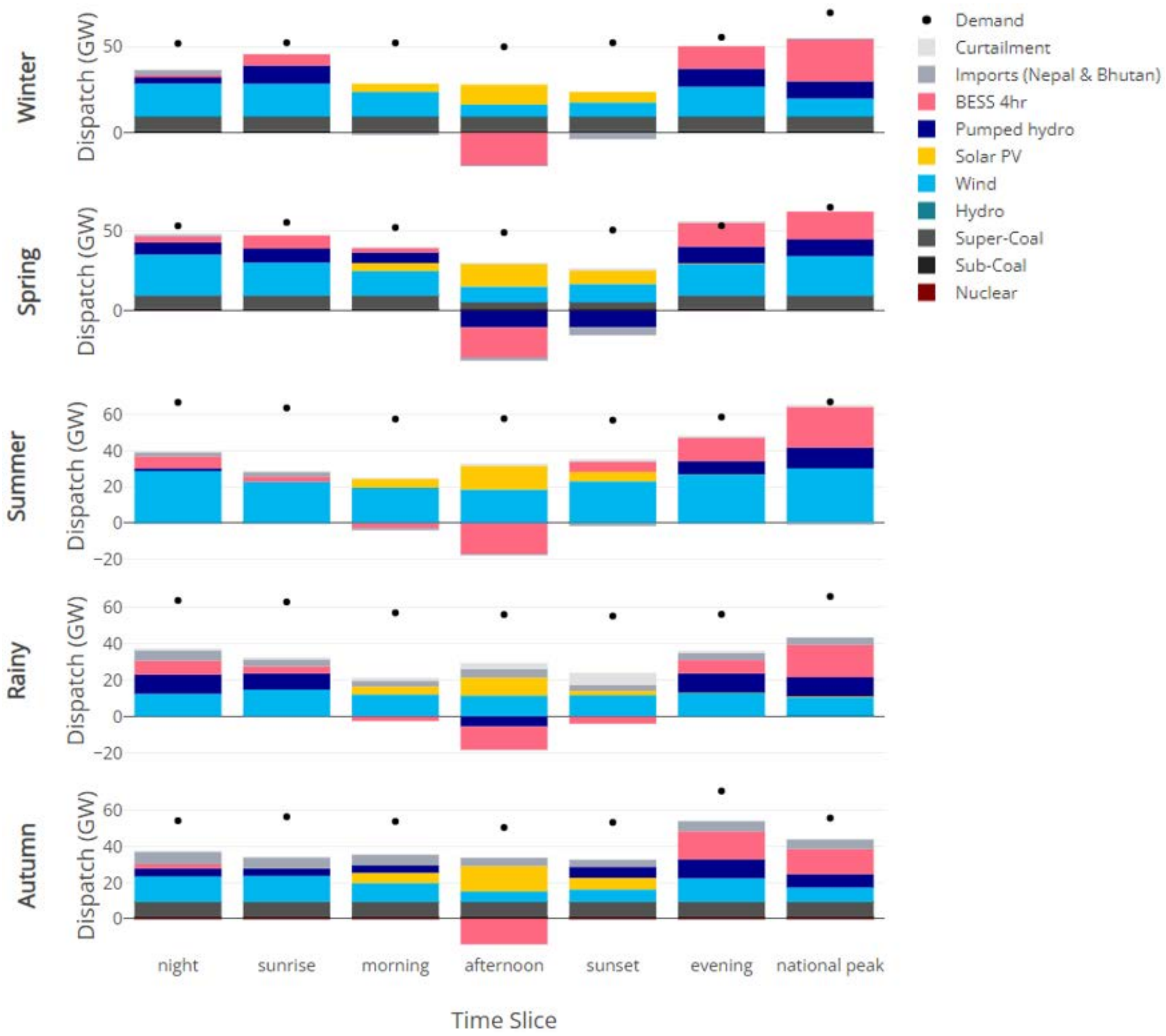

Figure 19. RE Policy scenario: Uttar Pradesh generation and demand by time slice (2050)

Note: Super-Coal = supercritical coal, Sub-Coal = subcritical coal. The negative dispatch values refer to charging of storage technologies (i.e., BESS, pumped hydro, etc.) or electricity exports. Y-axis scales are different.

4.3 Transmission

Similar to the Reference scenario, no new transmission investments occur between Uttar Pradesh and neighboring states or within Uttar Pradesh by 2030 in the RE Policy scenario. From 2030–2050, overall transmission investments between Uttar Pradesh and Rajasthan decrease from 32.5 GW in the Reference scenario to 27.3 GW in the RE Policy scenario. These transmission investments consist of 23.9 GW between the Agra DISCOM and Rajasthan, 2.2 GW between the Lucknow DISCOM and Rajasthan, and 1.2 GW between the Varanasi DISCOM and Rajasthan (Figure 20). Therefore, the decrease in transmission investment occurs solely in the Agra-Rajasthan corridor. Thus, the greater in-state generation in Uttar Pradesh and lower reliance on imports compared to the Reference scenario results in reduced transmission investments in the RE Policy scenario.

Figure 20. Reference scenario: Cumulative transmission investment (2030–2050)

4.4 System Costs

Total system costs in Uttar Pradesh, from 2023–2050, are approximately 15% higher in the RE Policy scenario compared to the Reference scenario (Figure 21). This is primarily because the higher capacity, fixed O&M, and operating reserve costs outweigh the lower transmission, variable O&M, and fuel costs. As a reminder, these state-level costs do not capture the power procurement cost or any future transmission fees for out-of-state power, which will be higher in the scenarios with more imports (i.e., the power procurement cost for Uttar Pradesh will be higher in the Reference scenario compared to the RE Policy scenario).

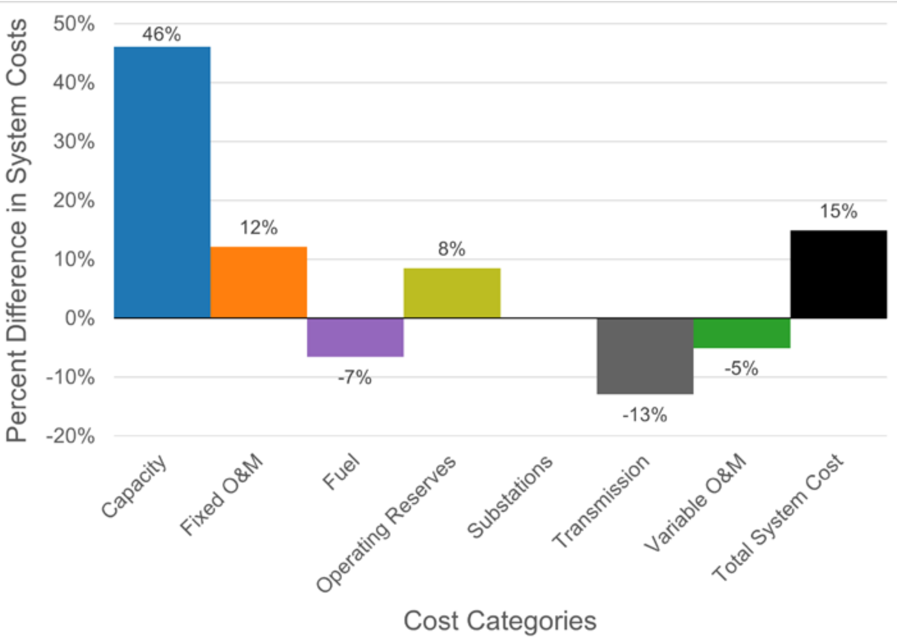

Figure 21. RE Policy scenario: Percentage difference in Uttar Pradesh system costs compared to the Reference scenario (2023–2050)

5 Green Hydrogen Scenario Results

The Government of India's Ministry of New and Renewable Energy has identified green hydrogen as a critical technology for achieving national goals of energy independence by 2047 and net-zero greenhouse gas emissions by 2070. The Ministry's National Green Hydrogen Mission is an action plan for India to establish a green hydrogen ecosystem that will enable the use of renewable energy resources across regions, seasons, and sectors, either as a fuel or as an industrial feedstock, by replacing fossil fuels in processes like petroleum refining, fertilizer production, and steel manufacturing (MNRE 2023). In support of the national mission and state economic goals, the Government of Uttar Pradesh has developed its own green hydrogen policy to promote growth, employment, and decarbonization. The policy includes a target to produce 1 MMT per year of green hydrogen/ammonia by 2028 (JMK Research & Analytics 2024).[8]

This study includes two scenarios that examine the impact of electricity demand for green hydrogen production based on the Uttar Pradesh policy. The first scenario (RE Policy, Baseline Green H_2) allows electricity demand for green hydrogen production to be met by the national grid, thus drawing from in-state or out-of-state renewables. The second scenario (RE Policy, Baseline Green H_2, Co-Located RE) requires electricity demand for green hydrogen production to be met by renewables that are co-located (i.e., in the same balancing area) with electrolyzers in Uttar Pradesh, without the use of co-located long-duration electricity and/or hydrogen storage. This scenario was developed to test whether such a strategy could be feasible for Uttar Pradesh, so the results do not serve as an endorsement of this approach or its likelihood of success. In reality, electricity demand for hydrogen production will most likely be met with a mix of power from the grid and power from co-located renewables, potentially paired with long-duration electricity and/or hydrogen storage. Nonetheless, these two scenarios serve as boundary conditions that could inform development in either direction.

For both green hydrogen scenarios, the baseline growth of green hydrogen production is estimated to reach 1.1 MMT in 2030 and 2.3 MMT in 2050. Electricity demand associated with these targets, based on assumed electrolyzer efficiencies, is shown in Table 3. More details about how these projections were developed can be found in Appendix A.2. The study also assumes that "green hydrogen" refers to hydrogen production from electrolyzers that use electricity generated by renewable energy resources (i.e., wind and solar PV), resulting in low or zero greenhouse gas emissions during production (Joshi, Chernyakhovskiy, and Chung 2022).

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[8] The modeling for this study is primarily based on UPNEDA's draft green hydrogen policy, released in 2023 (UPNEDA 2023). In March 2024, the Uttar Pradesh state government officially approved the policy, which has some differences compared to the 2023 draft (JMK Research & Analytics 2024). However, these policy modifications do not result in significant changes to the key model results and takeaways (see Appendix A.2 for more information).

Table 3. Projected Electricity Demand for Green Hydrogen Production in Uttar Pradesh

	2030	2035	2040	2045	2050
Green Hydrogen Production (MMT)	1.1	1.4	1.6	1.9	2.3
Electricity Requirement per MMT of Hydrogen (TWh/MMT)	48	48	48	48	48
Electricity Demand for Green Hydrogen Production (TWh)	53	65	76	90	110
Percentage Increase in Baseline Demand due to Green Hydrogen (%)	24%	23%	21%	21%	22%

5.1 First Green Hydrogen Scenario: Electricity From Grid

The first green hydrogen scenario (RE Policy, Baseline Green H_2) allows the additional electricity demand for green hydrogen production to be met by the grid. Therefore, this electricity demand could be met by in-state or out-of-state renewables. To represent this scenario in the model, the additional electricity demand for green hydrogen is added to the demand profile used in both the Reference and RE Policy scenarios. Although this method does not inherently guarantee that the electricity supplied to electrolyzers was generated by a renewable resource via an enforced model constraint, the results show that the incremental growth in nationwide renewable energy generation is greater than the incremental growth in electricity demand for green hydrogen. Therefore, there is sufficient renewable energy generation in neighboring states to meet Uttar Pradesh's in-state demand for green hydrogen. However, it is ultimately up to policymakers to decide whether relying on renewable energy imports, which the model shows to be technically feasible, is realistic for meeting most of the state's green hydrogen demand.

5.1.1 Capacity

Considering Uttar Pradesh's installed capacity for the 2023–2030 timeframe, the only difference between the RE Policy scenario and the RE Policy, Baseline Green H_2 scenario is the amount and type of BESS built. In the RE Policy scenario, approximately 1.5 GW of 2-hour BESS is installed in Uttar Pradesh by 2030. In the RE Policy, Baseline Green H_2 scenario, additional battery storage is not built in Uttar Pradesh until 2029, at which point there is just over 2 GW of 4-hour BESS in the state. From 2030–2050, the additional electricity demand for green hydrogen production has a small impact on Uttar Pradesh's in-state capacity and a larger impact on India's overall capacity. Figure 22 shows a difference plot comparing installed capacity in Uttar Pradesh in the RE Policy, Baseline Green H_2 scenario to the RE Policy scenario. By 2050, Uttar Pradesh has an additional 2.4 GW of 4-hour BESS—only a 1.7% increase in in-state capacity compared to the RE Policy scenario.

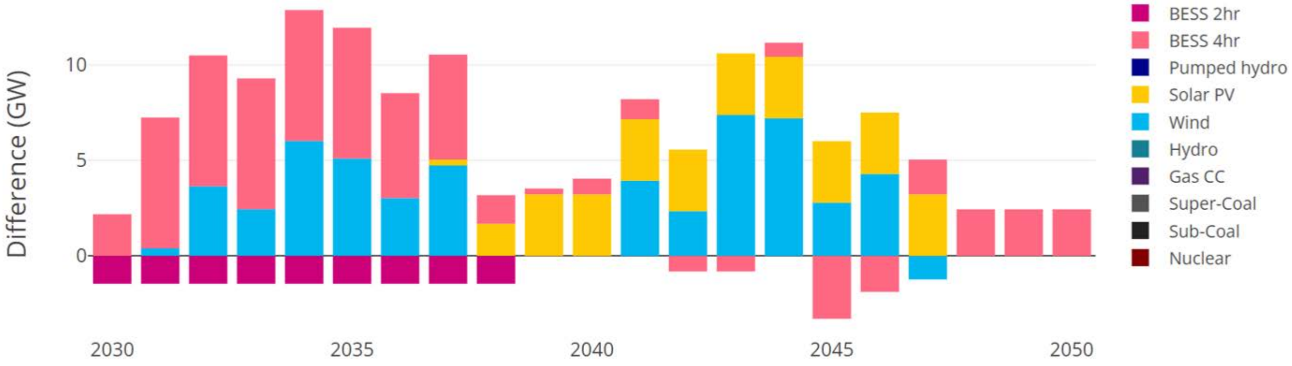

Figure 22. RE Policy, Baseline Green H_2 scenario: Difference in installed capacity in Uttar Pradesh compared to the RE Policy scenario (2030–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

Figure 23 shows the same comparison for all of India and conveys that the addition of green hydrogen production in Uttar Pradesh has a more notable impact on installed capacity in other Indian states. Overall, the nationwide capacity of wind, solar, and BESS increases by 31 GW, 28 GW, and 7 GW, respectively.

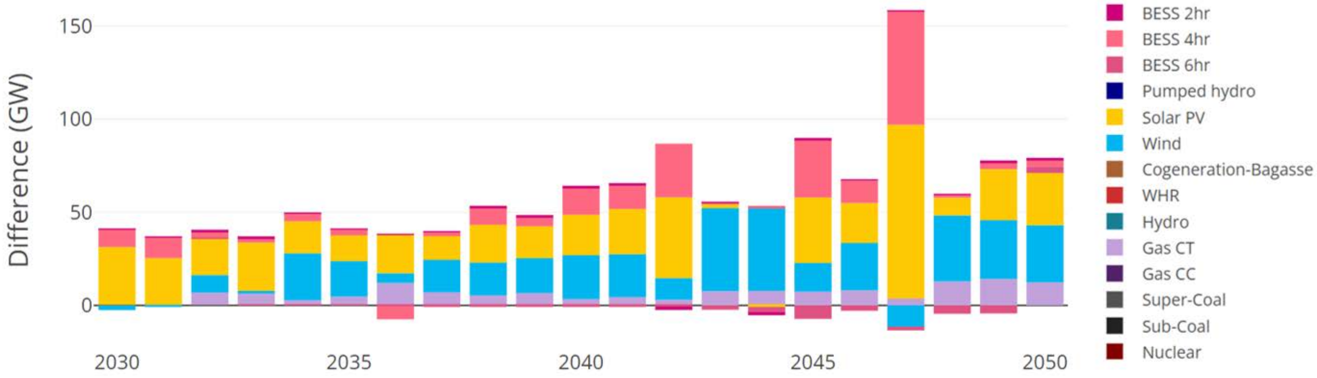

Figure 23. RE Policy, Baseline Green H_2 scenario: Difference in installed capacity in all of India compared to the RE Policy scenario (2030–2050)

Note: WHR = waste heat recovery, CT = combustion turbine, CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

These changes in national capacity are also shown at the state level in the following maps for wind (Figure 24), solar (Figure 25), and BESS (Figure 26). By 2050, wind capacity increases in Rajasthan (+11.4 GW), Andhra Pradesh (+7.8 GW), Maharashtra (+5.4 GW), Gujarat (+4.4 GW), and Karnataka (+1.7 GW), all states with high-quality wind resources. For solar PV, capacity increases in Maharashtra (+54.8 GW), Gujarat (+3.4 GW), Jammu and Kashmir (+3.0 GW), and Arunachal Pradesh (+2.8 GW), yet decreases in West Bengal (-9.6 GW), Rajasthan (-8.4 GW), Karnataka (-6.7 GW), Bihar (-4.2 GW), and Andhra Pradesh (-2.6 GW). Finally, 4-hour BESS capacity increases in Chhattisgarh (+9.1 GW), Nagaland (+5.7 GW), Madhya Pradesh (+3.5 GW), Uttar Pradesh (+2.4 GW), and Bihar (+1.6 GW), while decreasing in Telangana (-17.6 GW), Sikkim (-4.9 GW), Goa (-2.2 GW), Jharkhand (-1.9 GW), and Jammu and Kashmir (-1.3 GW).

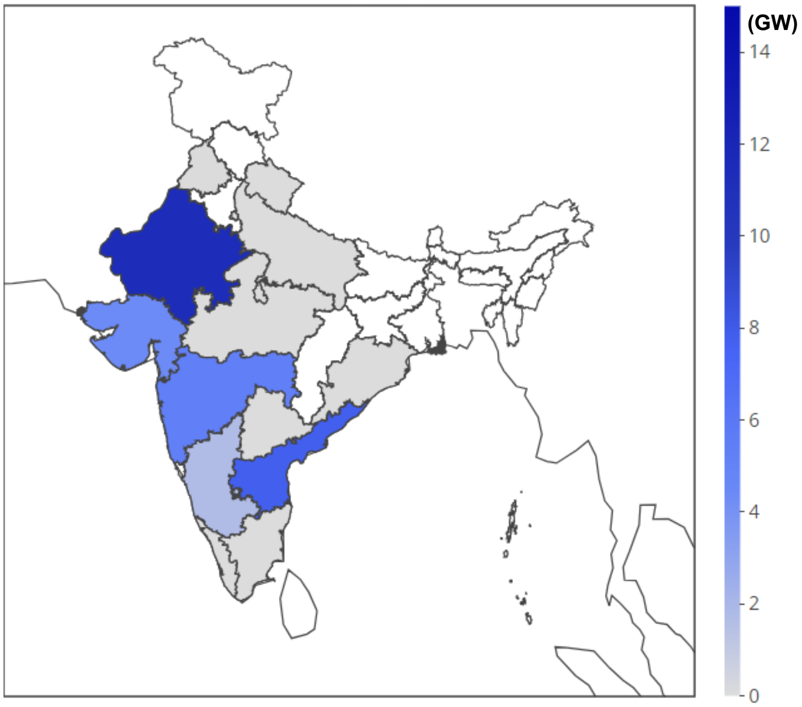

Figure 24. RE Policy, Baseline Green H_2 scenario: Increase in installed wind capacity in Indian states compared to the RE Policy scenario (2050)

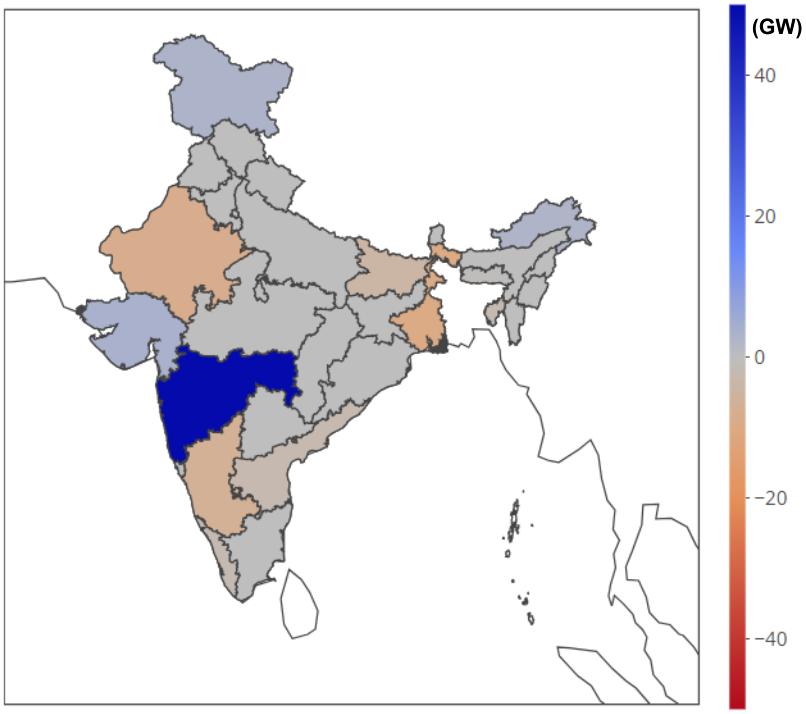

Figure 25. RE Policy, Baseline Green H_2 scenario: Difference in installed solar PV capacity in Indian states compared to the RE Policy scenario (2050)

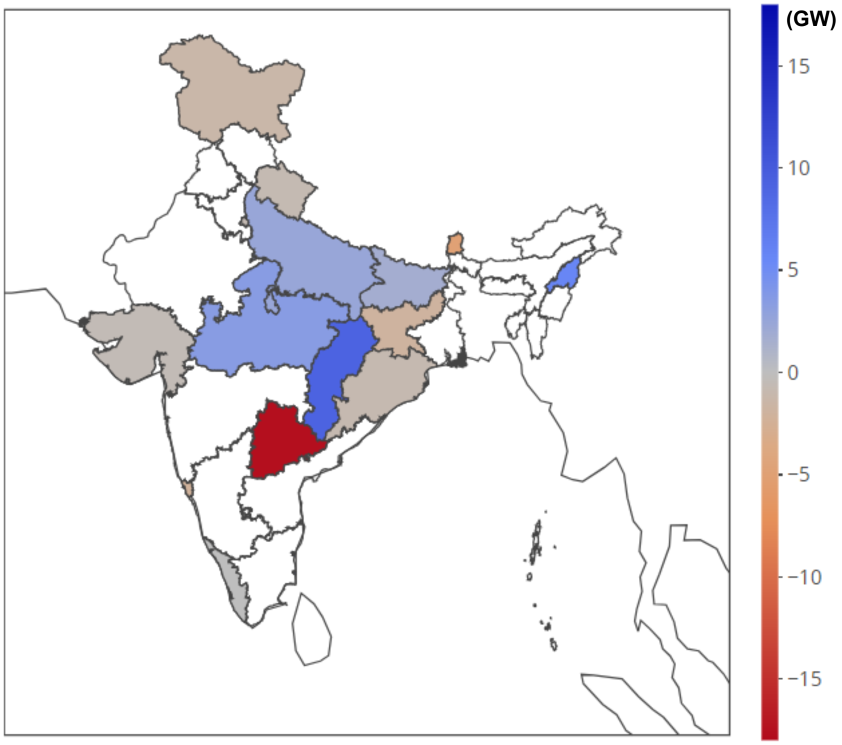

Figure 26. RE Policy, Baseline Green H_2 scenario: Difference in installed 4-hour BESS capacity in Indian states compared to the RE Policy scenario (2050)

5.1.2 Generation

Uttar Pradesh's generation profile for the 2023–2030 timeframe, like its in-state capacity profile for the same time period, is nearly identical to the RE Policy scenario, aside from some small changes due to the additional electricity demand for green hydrogen production. Looking to 2050, in-state generation of wind and solar PV increases slightly, but overall results indicate that meeting the additional electricity demand for green hydrogen with imports from other states remains cost-effective. Figure 27 shows a difference plot comparing electricity generation in Uttar Pradesh in the RE Policy, Baseline Green H_2 scenario to the RE Policy scenario, while Figure 28 shows the same comparison for all of India. By 2030, in-state solar PV generation increases by 1 TWh, nowhere close to covering the additional 53 TWh of green hydrogen-induced electricity demand. However, for all of India, 2030 solar PV generation increases by 55 TWh, covering the additional demand due to Uttar Pradesh's green hydrogen production. This same result, in which in-state renewable energy generation does not increase enough to cover Uttar Pradesh's electricity demand due to green hydrogen yet renewable energy generation across all of India increases sufficiently to meet this demand, also holds true in 2050.

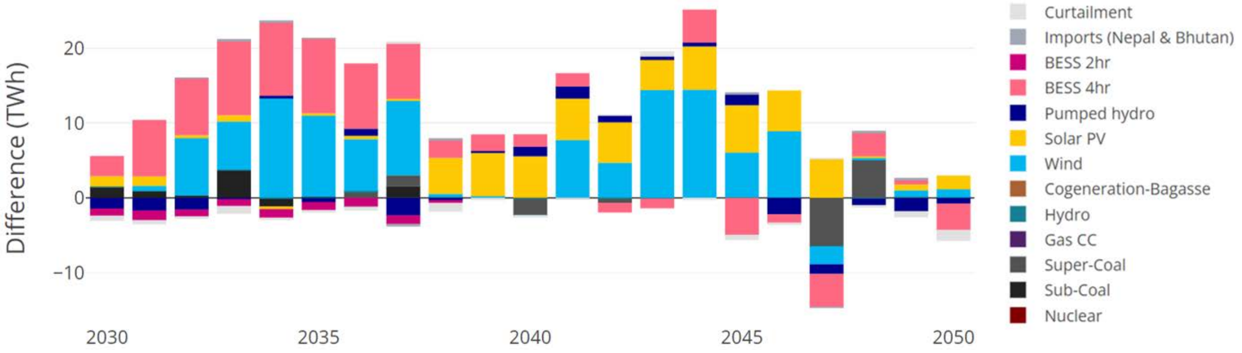

Figure 27. RE Policy, Baseline Green H_2 scenario: Difference in generation in Uttar Pradesh compared to the RE Policy scenario (2030–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

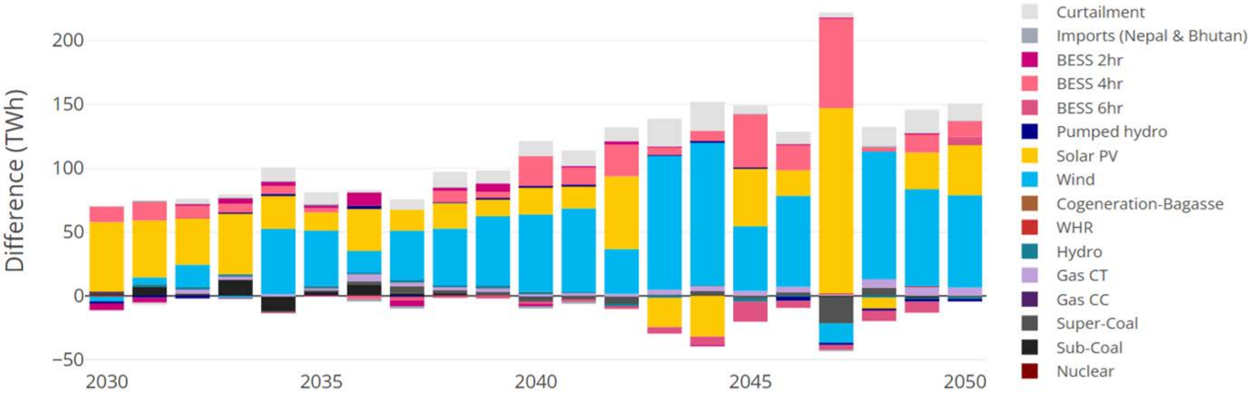

Figure 28. RE Policy, Baseline Green H_2 scenario: Difference in generation in all of India compared to the RE Policy scenario (2030–2050)

Note: WHR = waste heat recovery, CT = combustion turbine, CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal.

5.1.3 Transmission

Like the previous scenarios, no new transmission investments occur between Uttar Pradesh and neighboring states or within Uttar Pradesh by 2030. From 2030–2050, overall transmission investments between Uttar Pradesh and Rajasthan increase from 27.3 GW in the RE Policy scenario to 31.5 GW in the RE Policy, Baseline Green H_2 scenario (still lower than the 32.5 GW in the Reference scenario). These transmission investments consist of 29 GW between the Agra DISCOM and Rajasthan, 2 GW between the Lucknow DISCOM and Rajasthan, and 0.5 GW between the Varanasi DISCOM and Rajasthan.

Uttar Pradesh thus relies significantly on imports from Rajasthan across these first three scenarios (Reference, RE Policy, and RE Policy, Baseline Green H_2). Figure 29 shows that the electricity demand in Uttar Pradesh induced by green hydrogen in 2030 and 2050 is exceeded by the annual energy transmission between Rajasthan and Uttar Pradesh, which is exceeded by total excess wind and solar PV generation in Rajasthan that is exported to other states. Therefore, as India's overall renewable energy capacity (Section 5.1.1) and generation (Section 5.1.2) increase sufficiently to cover Uttar Pradesh's green hydrogen needs through 2050, this need could also be met by imports from Rajasthan. In fact, a similar study previously undertaken for Rajasthan showed that between 25% and 40% of electricity generation within Rajasthan in 2030 is exported to neighboring states, including Uttar Pradesh (Chernyakhovskiy et al. 2022).

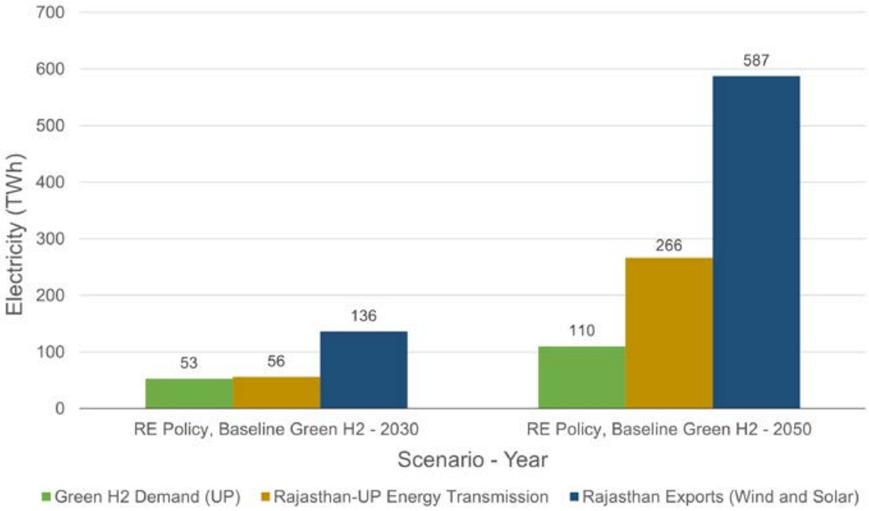

Figure 29. RE Policy, Baseline Green H_2 scenario: Annual energy transmission between Rajasthan and Uttar Pradesh vs. Uttar Pradesh green hydrogen demand (2030 and 2050)

Note: UP = Uttar Pradesh.

5.1.4 System Costs

The total system costs in Uttar Pradesh, from 2023–2050, are approximately 18% higher in the RE Policy, Baseline Green H_2 scenario compared to the Reference scenario (Figure 30). These costs are also roughly 3% higher than those in the RE Policy scenario, discussed in Section 4.4. As noted previously, these costs do not capture the power procurement cost or any future transmission fees for out-of-state power, which will be higher in scenarios with more imports.

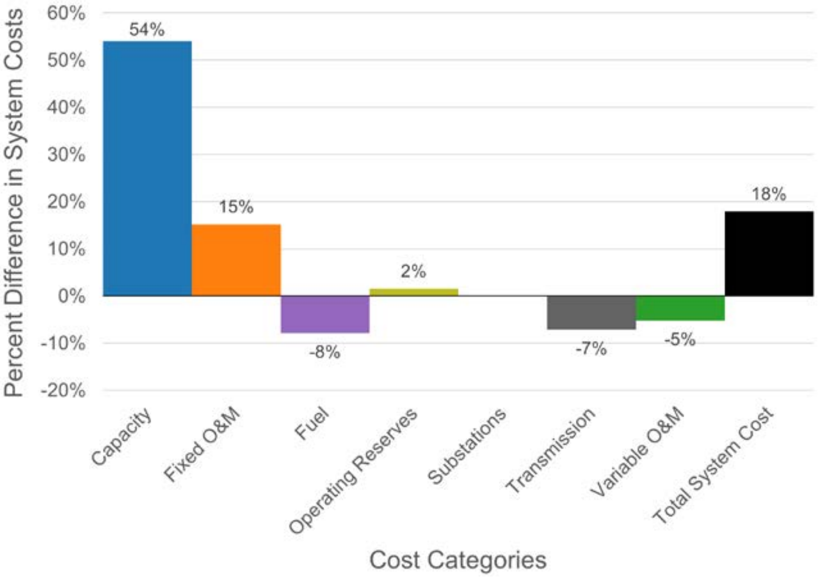

Figure 30. RE Policy, Baseline Green H_2 scenario: Percentage difference in Uttar Pradesh system costs compared to the Reference scenario (2023–2050)

5.2 Second Green Hydrogen Scenario: Electricity From Co-Located Renewables

The second green hydrogen scenario (RE Policy, Baseline Green H_2, Co-Located RE) requires that the additional electricity demand for green hydrogen production be met by in-state renewables that are co-located with electrolyzers. This scenario assumes that the electrolyzers cannot draw power from the grid or co-located long-duration energy storage to produce hydrogen and that there is no substantive hydrogen storage capacity in the state. However, the co-located renewables can export power that is not needed for hydrogen production to the grid. As stated earlier in the report, this hypothetical scenario was developed to test whether such a green hydrogen production strategy could be feasible for Uttar Pradesh.

To represent this scenario in the model, the additional electricity demand for green hydrogen production is included in a separate supply-demand constraint, and two new technology classes are created for meeting this demand: H_2 Solar PV and H_2 Wind. These two technology classes are identical to the Solar PV and Wind classes, except that they can only be built in Uttar Pradesh to satisfy the green hydrogen supply-demand constraint. The constraint requires total generation from these two technology classes to be greater than or equal to the electricity demand for green hydrogen production within each Uttar Pradesh balancing area, and allows excess generation to be exported to the grid.

5.2.1 Capacity

Unlike the first green hydrogen scenario (RE Policy, Baseline Green H_2), this scenario results in notable changes to Uttar Pradesh's capacity and generation mix by 2030, which become more significant by 2050. As shown in Figure 31, H_2 Wind starts to be built in 2024 and scales up quickly, with approximately 110 GW installed by 2030 and approximately 290 GW by 2050. There is also a smaller buildout of H_2 Solar PV beginning in 2025, reaching 3.1 GW by 2030 and 5.8 GW by 2050. In this scenario, no additional battery storage is installed in Uttar Pradesh by 2050. These results, disaggregated by balancing area, are shown in Figure 32. The Lucknow DISCOM has the largest installed capacity because of the higher green hydrogen demand assumed in that region (see Appendix A.2 for further details). The capacity of wind installed would likely be lower if paired with long-duration electricity and/or hydrogen storage to satisfy the green hydrogen demand. Various stakeholders and partners in Uttar Pradesh considered the rapid pace and large scale of the modeled wind investments to be unrealistic for the state.

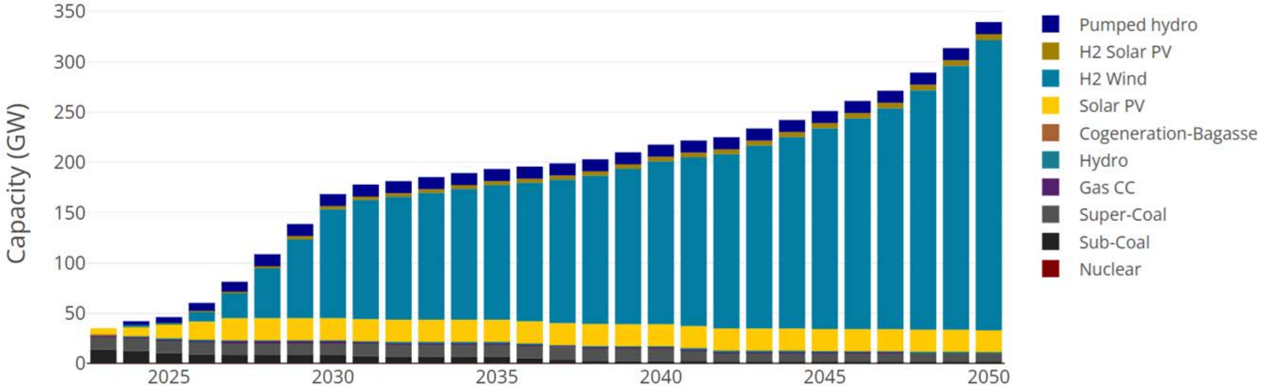

Figure 31. RE Policy, Baseline Green H_2, Co-Located RE scenario: Uttar Pradesh installed capacity (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. This result was considered unrealistic for Uttar Pradesh by various project stakeholders and partners, based on the rapid pace and large scale of the modeled wind investments.

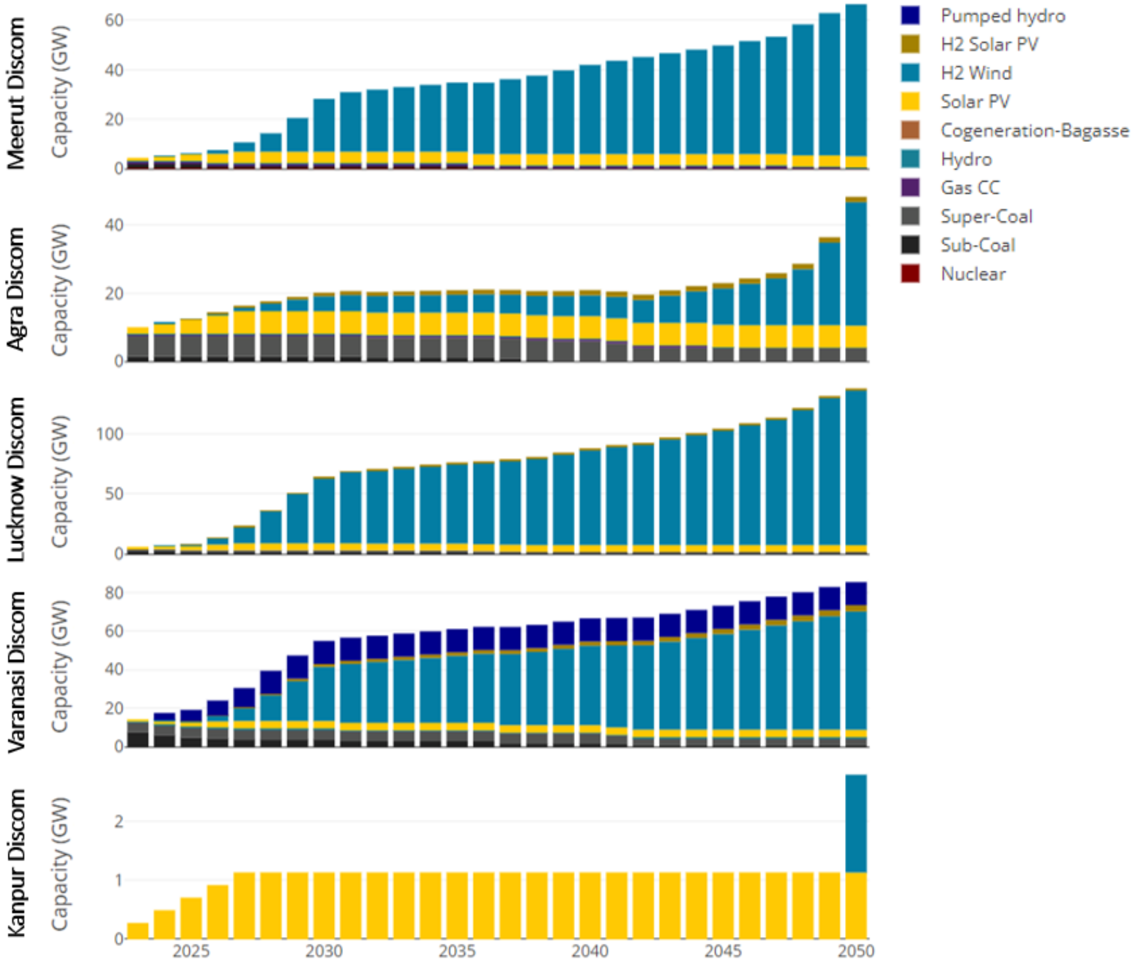

Figure 32. RE Policy, Baseline Green H_2, Co-Located RE scenario: Uttar Pradesh installed capacity by balancing area (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. This result was considered unrealistic for Uttar Pradesh by various project stakeholders and partners, based on the rapid pace and large scale of the modeled wind investments. Y-axis scales are different.

5.2.2 Generation

Uttar Pradesh's generation profile for the 2023–2050 timeframe in the RE Policy, Baseline Green H_2, Co-Located RE scenario is shown in Figure 33. Mostly due to the contributions of co-located H_2 Wind to the grid, Uttar Pradesh can meet most of its in-state demand with in-state resources. In-state generation can meet 97% of demand in 2030 and 94% of demand in 2050, with the rest being met by hydropower imports from Nepal. Overall, non-fossil generation meets 96% of the state's electricity demand in 2050. This result is a significant change from the other modeled scenarios, which show Uttar Pradesh relying heavily on imports.

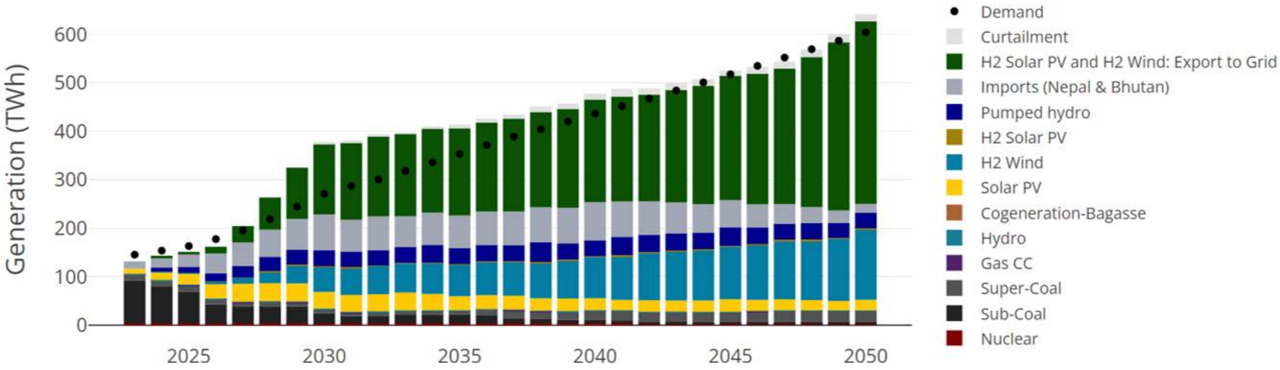

Figure 33. RE Policy, Baseline Green H_2, Co-Located RE scenario: Uttar Pradesh annual generation and demand (2023–2050)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. This result was considered unrealistic for Uttar Pradesh by various project stakeholders and partners, based on the rapid pace and large scale of the modeled wind investments.

In some time slices, excess generation from H_2 Wind is exported to neighboring states. This is because the H_2 Solar PV and H_2 Wind technologies are built to meet the hydrogen demand in all time slices, including the time slice with the lowest combined wind and solar resource. Thus, the technologies are overbuilt for most time slices, and generate more electricity than needed to just serve the hydrogen demand. Figure 34 shows the generation and demand by time slice in 2030. The "Autumn: afternoon" time slice has the lowest amount of excess H_2 Solar PV and H_2 Wind generation in 2030, shown in the figure as "H_2 Solar PV and H_2 Wind: Export to Grid." Therefore, these technologies are built to ensure that the hydrogen demand, which is constant across all time slices, can be met in the "Autumn: afternoon" period, which is the period with the lowest combined renewable energy resource. In practice, there may be opportunities to contract for out-of-state renewables (Section 5.1) in combination with adjusting the demand for hydrogen production to align electricity demand with the timing of in-state renewable resource availability (i.e., by using long-duration electricity and/or hydrogen storage, thus resulting in lower required capacities of co-located renewables). However, assessing the potential for flexible hydrogen demand in Uttar Pradesh is outside the scope of this study.

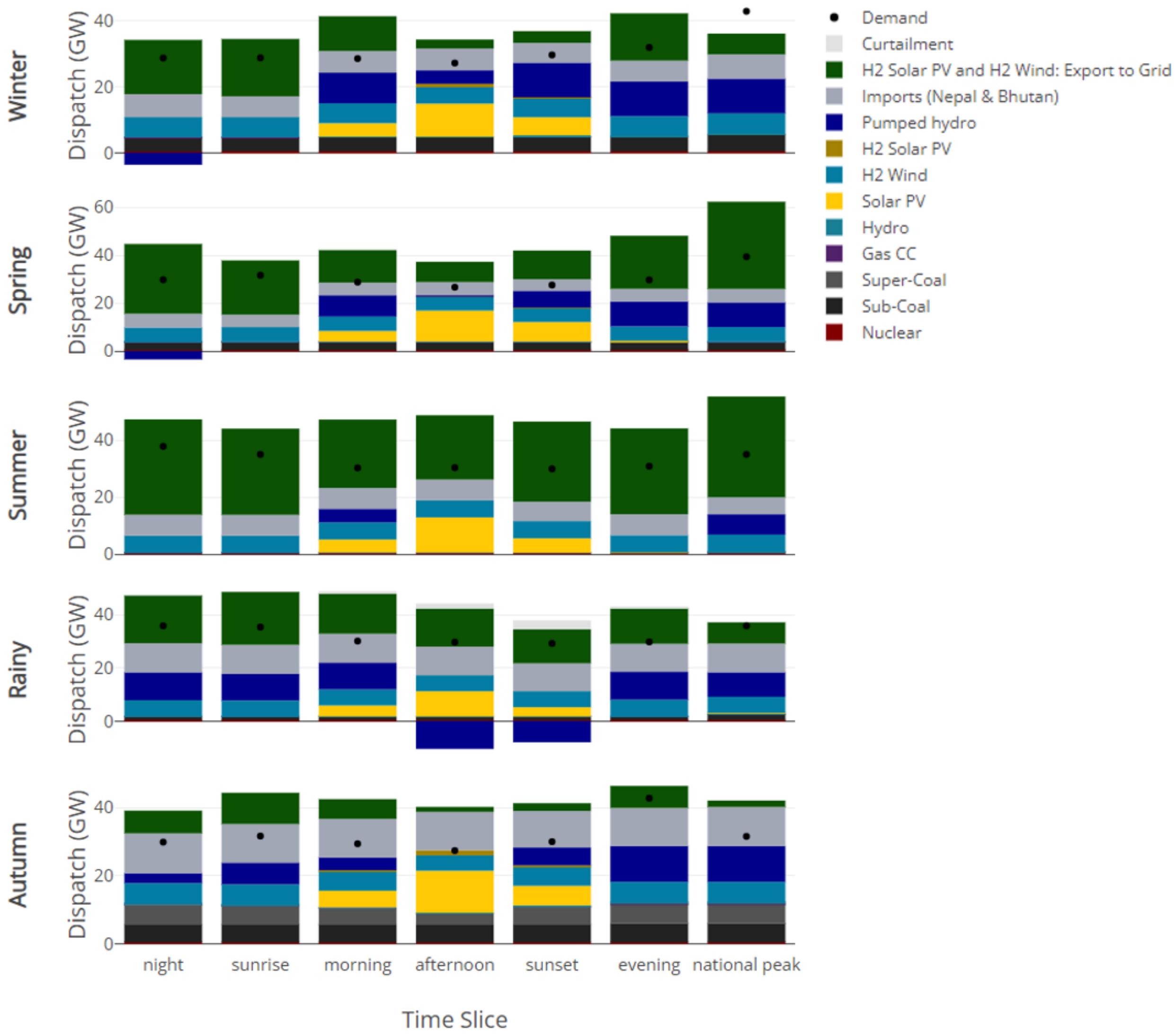

Figure 34. RE Policy, Baseline Green H_2, Co-Located RE scenario: Uttar Pradesh generation and demand by time slice (2030)

Note: CC = combined cycle, Super-Coal = supercritical coal, Sub-Coal = subcritical coal. This result was considered unrealistic for Uttar Pradesh by various project stakeholders and partners, based on the rapid pace and large scale of the modeled wind investments. Y-axis scales are different.

Similar patterns are shown in the dispatch plot for 2050 (Figure 35). However, there are more time slices in 2050 in which Uttar Pradesh relies on electricity imports compared to 2030, particularly in autumn. This is because, as mentioned earlier, the state's reliance on imports increases from 3% of annual demand in 2030 to 6% in 2050, which is still significantly less compared to the RE Policy, Baseline Green H_2 scenario.

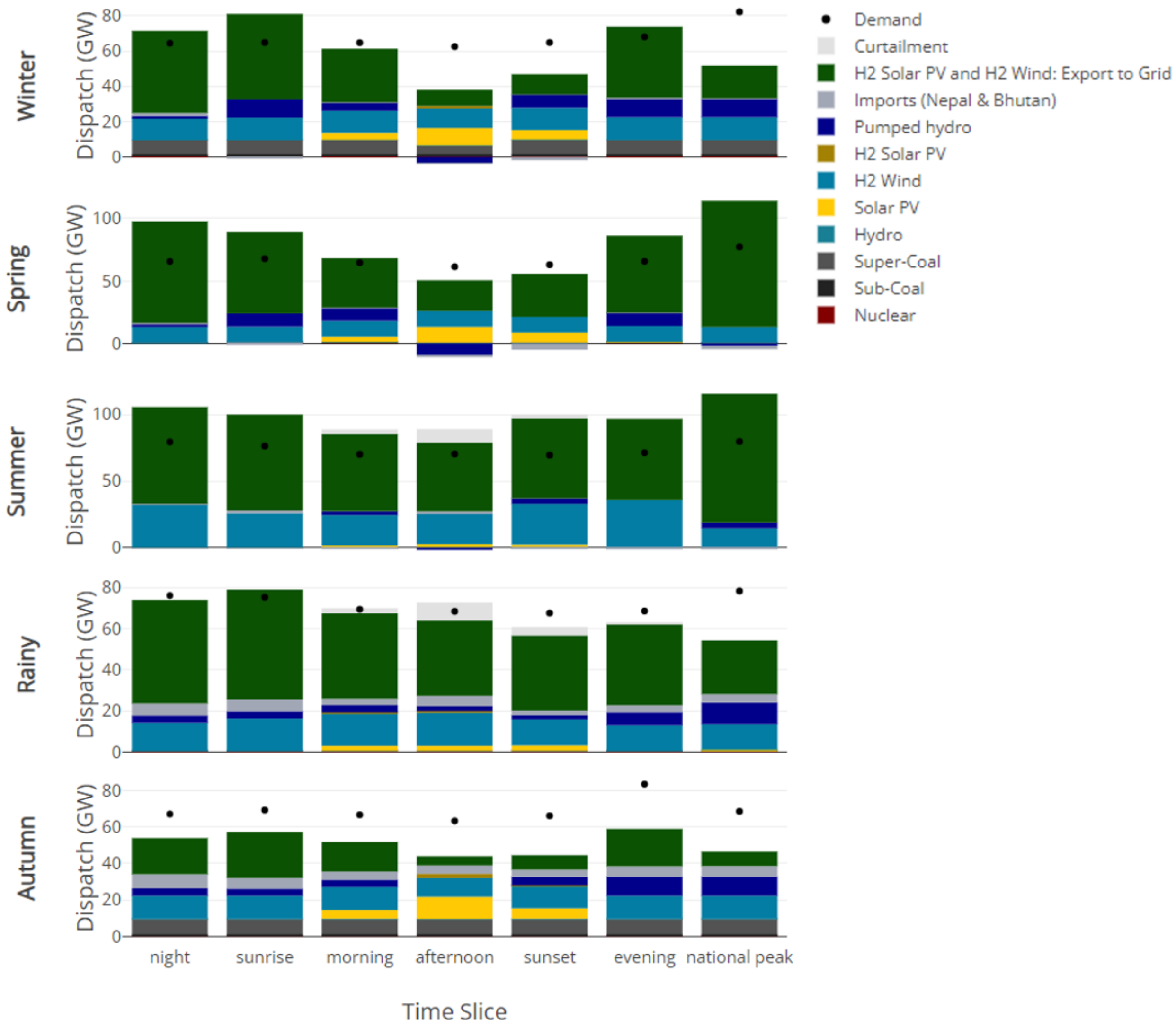

Figure 35. RE Policy, Baseline Green H_2, Co-Located RE scenario: Uttar Pradesh generation and demand by time slice (2050)

Note: Super-Coal = supercritical coal, Sub-Coal = subcritical coal. This result was considered unrealistic for Uttar Pradesh by various project stakeholders and partners, based on the rapid pace and large scale of the modeled wind investments. Y-axis scales are different.

5.2.3 Transmission

Unlike the other scenarios in this study, the RE Policy, Baseline Green H_2, Co-Located RE scenario does not result in any additional transmission investments by 2050 between Uttar Pradesh and other states or within Uttar Pradesh. This is likely because Uttar Pradesh's reliance on imports substantially decreases, and thus the large transmission investments between the state and Rajasthan are no longer needed. This could be a reason why the transmission investments nationally instead show a large increase in capacity between Rajasthan and Madya Pradesh to its south, which is a likely destination for Rajasthan's renewable energy exports.

5.2.4 System Costs

With the extensive buildout of H_2 Wind capacity to meet electricity demand for green hydrogen production across all seasons, system costs in the RE Policy, Baseline Green H_2, Co-Located RE scenario are approximately 82% higher from 2023–2050 compared to the RE Policy, Baseline Green H_2 scenario (Figure 36). As noted previously, these costs do not capture the power procurement cost or any future transmission fees for out-of-state power, which will be higher in the scenarios with more imports (i.e., the power procurement cost will be higher in the RE Policy, Baseline Green H_2 scenario compared to the RE Policy, Baseline Green H_2, Co-Located RE scenario). This result also does not capture potential subsidies and incentives for green hydrogen projects, which would reduce the relative costs of this scenario.

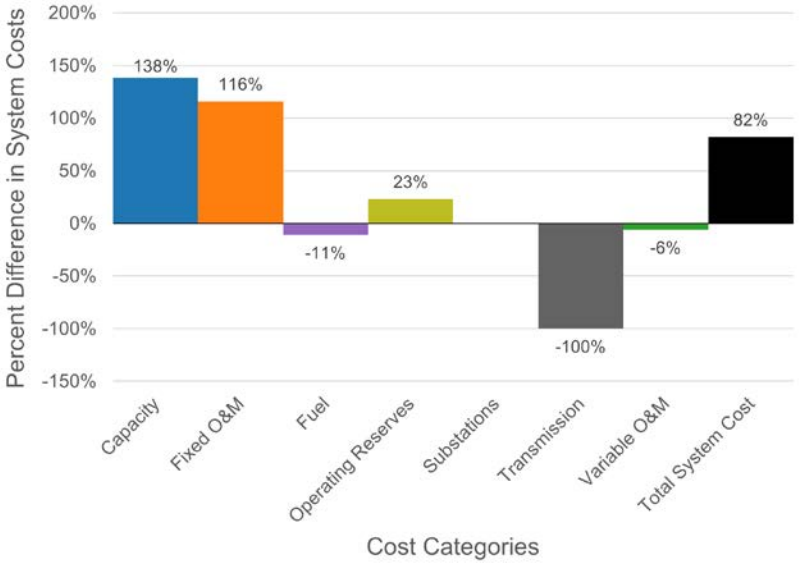

Figure 36. RE Policy, Baseline Green H_2, Co-Located RE scenario: Percentage difference in Uttar Pradesh system costs compared to the RE Policy, Baseline Green H_2 scenario (2023–2050)

6 Key Takeaways

National and state-level policies are anticipated to cause significant changes in Uttar Pradesh's power sector over the next few decades, in terms of both supply (e.g., increases in renewable energy capacity) and demand (e.g., increases in green hydrogen production). While Uttar Pradesh's renewable energy and green hydrogen targets are based on a near-term vision (out to 2030), it is also important to understand the impacts over a longer time horizon (out to 2050). Therefore, this section is divided into near-term and long-term key takeaways for energy policymakers and planners in Uttar Pradesh, who can use these findings to anticipate and proactively respond to potential changes in the power system.

6.1 Near-Term (2024 – 2030)

1. UPNEDA's policy targets drive the adoption of renewables (22 GW of solar PV) and storage (1.5 GW–2.2 GW of BESS and 12 GW of pumped hydro) by 2030.
2. Uttar Pradesh increasingly relies on low-cost electricity imports (70%–84% of in-state demand in 2030) in all scenarios except when renewables are co-located for green hydrogen production, although the policy targets for solar PV and pumped hydro result in a more diverse in-state resource mix and reduce the state's reliance on imports compared to the Reference scenario.
3. It is more cost-effective and technically feasible to meet most of Uttar Pradesh's anticipated green hydrogen demand (53 TWh in 2030) with contracts or other procurement mechanisms for out-of-state wind and solar PV, primarily from Rajasthan, although this increases the state's reliance on imports in 2030 by almost 50 TWh compared to the Reference scenario. Thus, it is up to state policymakers to ultimately determine whether it is realistic to rely on electricity imports for most of Uttar Pradesh's green hydrogen production needs.
4. Although coal capacity remains relatively constant across all scenarios through 2030, it is cost-effective to decrease coal utilization on an annual basis and in particular seasons (i.e., rainy and summer seasons) to provide flexibility for renewable energy imports.
5. If co-located renewables (without co-located long-duration electricity and/or hydrogen storage) meet all of Uttar Pradesh's green hydrogen demand by 2030 instead of mostly imports, this results in a rapid and large buildout of wind (108 GW by 2030), and in-state generation meets almost all the demand (97% in 2030). Due to the pace and scale of wind investments required, various stakeholders and partners in Uttar Pradesh considered that the approach of meeting the state's green hydrogen demand solely through co-located renewables is not feasible.
6. No new transmission investments occur for Uttar Pradesh through 2030 in any of the scenarios, indicating that the current and planned transmission capacity is sufficient in the near term (based on data available in the model).

6.2 Long Term (2030–2050)

1. Wind capacity starts to be built roughly when its capital cost dips below 6 INR Crore/MW, BESS capacity starts to be built roughly when its capital cost dips below 5

INR Crore/MW, and solar PV capacity starts to be built economically (i.e., without policy mandates) roughly when its capital cost dips below 4 INR Crore/MW.

2. As a percentage of its annual demand, Uttar Pradesh's reliance on imports decreases across most scenarios from 2030–2050 (from 70%–84% of annual demand to 56%–61%) due to the significant generation contribution from low-cost wind in the Meerut DISCOM, assuming that electricity imports serve almost all of the green hydrogen demand.
3. It is more cost-effective and technically feasible to meet most of Uttar Pradesh's anticipated green hydrogen demand (110 TWh in 2050) with contracts or other procurement mechanisms for out-of-state wind and solar PV, primarily from Rajasthan, although this increases the state's reliance on imports in 2050 by almost 64 TWh compared to the Reference scenario. Thus, it is up to state policymakers to ultimately determine whether it is realistic to rely on electricity imports for most of Uttar Pradesh's green hydrogen production needs.
4. If co-located renewables (without co-located long-duration electricity and/or hydrogen storage) meet all of Uttar Pradesh's green hydrogen demand by 2050 instead of mostly imports, this results in a rapid and large buildout of wind (289 GW by 2050), and in-state generation meets almost all the demand (94% in 2050). Due to the pace and scale of wind investments required, various stakeholders and partners in Uttar Pradesh considered that the approach of meeting the state's green hydrogen demand solely through co-located renewables is not feasible.
5. Significant transmission investments occur between Uttar Pradesh and Rajasthan (27 GW–33 GW), assuming that electricity imports serve almost all of the green hydrogen demand.
6. Over 90% of Uttar Pradesh's electricity demand in 2050 could be met by non-fossil generation across all scenarios, assuming that the electricity imports would be met by out-of-state clean energy resources.

6.3 Summary

Regarding Uttar Pradesh's increase in renewable energy capacity, the buildout of solar PV and pumped hydro is almost entirely driven by state targets. Wind, however, is shown to be cost-competitive starting in the 2030s, roughly when its capital cost dips below 6 INR Crore/MW (Figure 5) and due to different assumptions about commercially viable wind speeds and capacity factors compared to other assessments (Text Box 1). Wind greatly exceeds the installed capacity of solar PV, which is not economically built until roughly when its capital cost dips below 4 INR Crore/MW. Because Uttar Pradesh is not traditionally considered a high-wind state by stakeholders in India, policymakers could further investigate wind resource potential in the state to be prepared for potentially favorable economics starting in the 2030s. For example, possible actions could include collecting data on wind speeds in the Meerut DISCOM area, which did not contain any wind monitoring stations in the most recent assessment from India's National Institute of Wind Energy (NIWE 2023), to validate the model results shown in Figure 2. The results also include the buildout of 4-hour BESS roughly when its capital cost dips below 5 INR Crore/MW. Therefore, state decision makers can consider including both wind energy and BESS in future clean energy targets and policies.

Uttar Pradesh can also meet the anticipated electricity demand for green hydrogen production. The two hydrogen-specific scenarios considered in this study represent opposite ends of a spectrum for planning approaches. One scenario (RE Policy, Baseline Green H_2) shows that it is technically possible, although ultimately dependent on state priorities, to meet most of the green hydrogen demand with out-of-state renewables, resulting in lower total system costs and a higher reliance on imports. Another scenario (RE Policy, Baseline Green H_2, Co-Located RE), which was developed as a hypothetical test case, shows that meeting the green hydrogen demand entirely with co-located renewables and no co-located long-duration electricity or hydrogen storage results in an extremely rapid and large buildout of wind capacity. This result was not considered feasible by stakeholders in Uttar Pradesh. Therefore, a potential path forward for Uttar Pradesh likely involves some combination of these two approaches, in which the state relies on both in-state and out-of-state renewables, as well as the possibility of long-duration electricity and/or hydrogen storage to enhance flexibility, in order to meet its green hydrogen production targets while considering the trade-offs between cost and energy security (Figure 37).

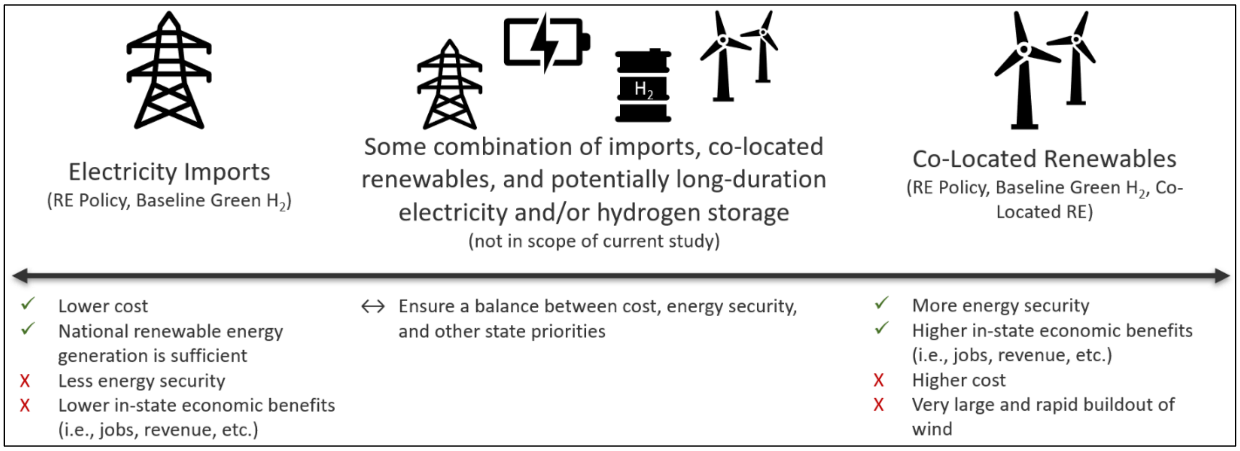

Figure 37. Spectrum of potential approaches to meet Uttar Pradesh's green hydrogen targets

6.4 Limitations and Next Steps

These insights provide a snapshot of trends that can be projected at the time of this publication, using the available data. Modeling results can evolve as the landscape of policies, regulations, and technology costs evolve over time. Therefore, the underlying assumptions, data, methods, tools, and analyses described in this study can be periodically revisited and used as a framework for future planning studies in Uttar Pradesh as well as other Indian states and union territories.

Regarding limitations, this study does not optimize costs for Uttar Pradesh specifically but rather for India as a whole, and it does not consider potential green hydrogen policies of other states in India and the possible impact those could have on the national energy mix. Due to data limitations, the study also did not look at impacts on intra-state transmission (i.e., transmission within Uttar Pradesh and its respective DISCOMs) in detail. Furthermore, the amount of green hydrogen production allocated to Uttar Pradesh in the CEA's 20th Electric Power Survey demand projections was unknown and the second green hydrogen scenario (RE Policy, Baseline Green H_2, Co-Located RE) does not account for the potential of long-duration electricity or hydrogen storage, supported by flexible electrolyzer operation, to reduce the capacity of co-located renewables required for green hydrogen production. Finally, this study is a forward-looking assessment and finds that wind resources are potentially viable in Uttar Pradesh starting in the 2030s. Several present-day assessments of the state's wind resource, which use different assumptions about commercially viable wind plants, find that wind power is not currently commercially attractive in Uttar Pradesh, a conclusion that is supported by the ReEDS-India model results for the 2020s (see Text Box 1 for further details).

Further analysis can examine the potential impacts of long-duration electricity and/or hydrogen storage as part of Uttar Pradesh's strategy to meet its green hydrogen targets with enhanced flexibility (i.e., storing excess electricity during high-wind or high-solar time periods for later use in electrolyzers or storing excess hydrogen generated by flexibly-operated electrolyzers during high-wind or high-solar time periods for later use by consumption facilities). Future work can also examine the impacts of incentives contained in Uttar Pradesh's green hydrogen policy or allocate green hydrogen production to DISCOMs based on renewable energy resource quality instead of fertilizer plant and refinery locations (Appendix A.2). The results of this study are also used in an air quality analysis to assess the pollution and health impacts of the long-term planning trajectories studied here (Ravi et al., 2024).

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Appendix A. Additional Model Assumptions

A.1 Solar PV Policy Assumptions

UPNEDA's solar PV policy does not include capacity targets by DISCOM within the state. Thus, the state-level capacity targets (14 GW of utility-scale PV and 8 GW of distributed PV by the end of 2027) are proportionately allocated to each DISCOM based on the technical potential of solar PV in that DISCOM, which was determined using the solar resource data (Figure 3) and NREL's Renewable Energy Potential model (Maclaurin et al. 2021). For example, the Agra DISCOM accounts for approximately 39% and 14% of the available utility-scale and distributed solar PV technical potential in Uttar Pradesh, respectively. Thus, 39% of the utility-scale solar PV prescriptions and 14% of the distributed solar PV prescriptions are assigned to the Agra DISCOM. These percentages are shown for all DISCOMs in Table A-1.

Table A-1. Percentage of Solar PV Technical Potential Capacity by Uttar Pradesh Balancing Area

	Percentage of Technical Potential Capacity	
	Utility-Scale Solar PV	**Distributed Solar PV**
Agra DISCOM	39%	14%
Kanpur DISCOM	0.3%	14%
Lucknow DISCOM	31%	17%
Meerut DISCOM	8%	45%
Varanasi DISCOM	22%	11%

A.2 Green Hydrogen Policy Assumptions

The CEA's 20th Electric Power Survey assumes that an unspecified portion of the electricity demand projection for Uttar Pradesh is due to green hydrogen production (CEA 2022). This is based on India's national-level targets for green hydrogen production, with the electricity demand to meet these targets allocated to states based on the proportion of high-tension industrial electricity demand in the states (i.e., if Uttar Pradesh accounts for 20% of high-tension industrial electricity demand in India, then it will be allocated 20% of the assumed electricity demand for green hydrogen production). Electricity demand for green hydrogen production allocated to each state is then divided among the state's DISCOMs using the same method. At the DISCOM level, it is assumed that 50% of this green hydrogen demand will be met by grid-connected renewables and 50% will be met by captive power plants co-located with electrolyzers. The primary demand projections in the CEA report include only the former half (grid-connected renewables), while the latter half (captive power plants co-located with electrolyzers) is included in Chapter 7 of their report. However, the exact amount of green hydrogen demand attributed to Uttar Pradesh each year in either set of projections is not specified. The CEA report also does not appear to account for Uttar Pradesh's state-level green hydrogen targets. The Reference scenario and the RE Policy scenario therefore assume that no additional green hydrogen will be produced in the state beyond what is already assumed by the CEA. The two green hydrogen scenarios in Section 5 do include electricity demand projections for additional green hydrogen production.

These projections were developed by RMI based on UPNEDA's policy for green hydrogen, production and capacity data for fertilizer plants and refineries in Uttar Pradesh that consume hydrogen as a feedstock, assumed electrolyzer efficiencies and trends, and stakeholder input (Table 3). For both green hydrogen scenarios (RE Policy, Baseline Green H_2 and RE Policy, Baseline Green H_2, Co-Located RE), the total annual electricity demand for green hydrogen is divided evenly across the 35 time slices, such that each representative hour has the same demand value, and is divided by DISCOM based on the locations of existing and anticipated fertilizer plants and refineries. The proportion of hydrogen production assigned to each Uttar Pradesh DISCOM is assumed to remain constant over the time horizon of the model (Table A-2).

Table A-2. Proportion of Green Hydrogen Production Assigned to Each Uttar Pradesh Balancing Area

	Proportion
Agra DISCOM	9%
Kanpur DISCOM	0%
Lucknow DISCOM	44%
Meerut DISCOM	14%
Varanasi DISCOM	33%

Using this methodology, RMI developed three projections for green hydrogen production in Uttar Pradesh to account for possible variation in future hydrogen growth: Baseline, Moderate, and High. The Baseline scenario assumes the lowest levels of green hydrogen production, reaching 1.1 MMT in 2030 and 2.3 MMT in 2050. The High scenario assumes the highest levels of green hydrogen production, reaching 1.3 MMT in 2030 and 3.0 MMT in 2050, while the Moderate scenario assumes a growth rate in-between the Baseline and High scenarios. This study uses the Baseline projection throughout because the CEA's 20th Electric Power Survey already assumes some unspecified quantity of green hydrogen production in Uttar Pradesh in its electricity demand projections, which are also used in this study. Therefore, utilizing the Baseline green hydrogen projection throughout can help avoid overestimating the electricity demand in Uttar Pradesh attributed to green hydrogen and is likely closer to the Moderate scenario in reality.

Text Box 2. Are there changes to the model results when accounting for Uttar Pradesh’s approved green hydrogen policy, released in March 2024?

Due to the project timeline, the modeling for this study is based on UPNEDA’s draft green hydrogen policy, released in 2023 (UPNEDA 2023). In March 2024, as this report neared publication, the Uttar Pradesh state government officially approved the green hydrogen policy, which has some differences compared to the 2023 draft (JMK Research & Analytics 2024). The approved policy sets a green hydrogen production target of 1 MMT by 2028, up from the 0.5 MMT by 2028 target in the draft policy. The approved policy also does not set any production targets for 2030. Based on the goals stated in the draft policy (i.e., for Uttar Pradesh to be a 100% green hydrogen and green ammonia consuming state by 2030), this study assumes green hydrogen production values of 1.1 MMT by 2030 and 2.3 MMT by 2050. These values could be slightly higher if considering the approved 2024 policy.

However, the policy modifications do not result in major changes to the key model results and takeaways. This study assumes that green hydrogen production reaches 1 MMT just 1–2 years after the targets specified in the approved policy. Furthermore, **the increase in total electricity demand in Uttar Pradesh does not increase significantly in 2028 (11%), 2030 (3%), or 2050 (5%)** when accounting for the approved policy and extrapolated trends, compared to the 2023 draft. To evaluate potential differences, NREL re-ran the model using assumptions based on the approved UPNEDA green hydrogen policy for the RE Policy, Baseline Green H_2 scenario. Results show there is **an increase of 0.6 GW of BESS (1% of total capacity) in 2028, an increase of 4.3 GW of BESS (7% of total capacity) in 2030, a decrease of 3.7 GW of BESS (4% of total capacity) in 2040, and an increase of 5.0 GW of solar PV and 1.0 GW of BESS (4% of total capacity) in 2050** (Figure A-1). Uttar Pradesh meets most of the relatively small increase in total electricity demand (if considering the 2024 approved policy instead of the 2023 draft policy) with more imports.

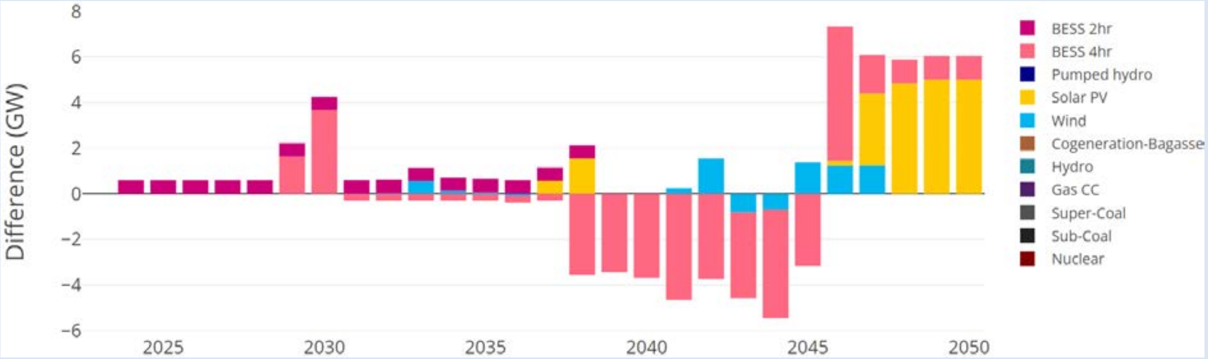

Figure A-1. RE Policy, Baseline Green H_2 scenario: Difference in installed capacity in Uttar Pradesh using the 2024 approved policy compared to the 2023 draft policy

One result that could change is the cost of the Co-Located RE scenario because **the model does not include the subsidies for green hydrogen projects included in the approved policy**. These subsidies would reduce the cost difference between the scenario with co-located renewables for green hydrogen production and the other scenarios, which could potentially improve the economics and feasibility of utilizing co-located renewables for some portion of Uttar Pradesh’s anticipated green hydrogen demand. Additional scenarios and cost assumptions, based on the approved policy, could be explored in future modeling efforts.

A.3 Nepal Imports Assumptions

Because the ReEDS-India model does not distinguish between transmission owned by the state (i.e., Uttar Pradesh Power Corporation Limited) and transmission owned by the central government (i.e., Inter State Transmission System), imports from Nepal are counted toward meeting Uttar Pradesh's electricity demand. The capacity of Nepal hydropower available for import into Uttar Pradesh (Lucknow DISCOM and Varanasi DISCOM), along with the seasonal capacity factors for this hydropower, are exogenously defined based on assumptions in the ReEDS-India model. Nepal's buildout of future hydropower capacity through 2040, which includes a mix of run-of-river and reservoir hydropower, is based on the Transmission System Development Plan of Nepal (RPGCL 2018). Additional details about the methodology used to represent India's future imports of hydropower from Nepal are available in Chernyakhovskiy et al. (2021).