Impacts of Renewable Energy and Green Hydrogen Policies on Uttar Pradesh's Power Sector Future: *Additional Modeling Scenarios to Explore Hydrogen Flexibility*

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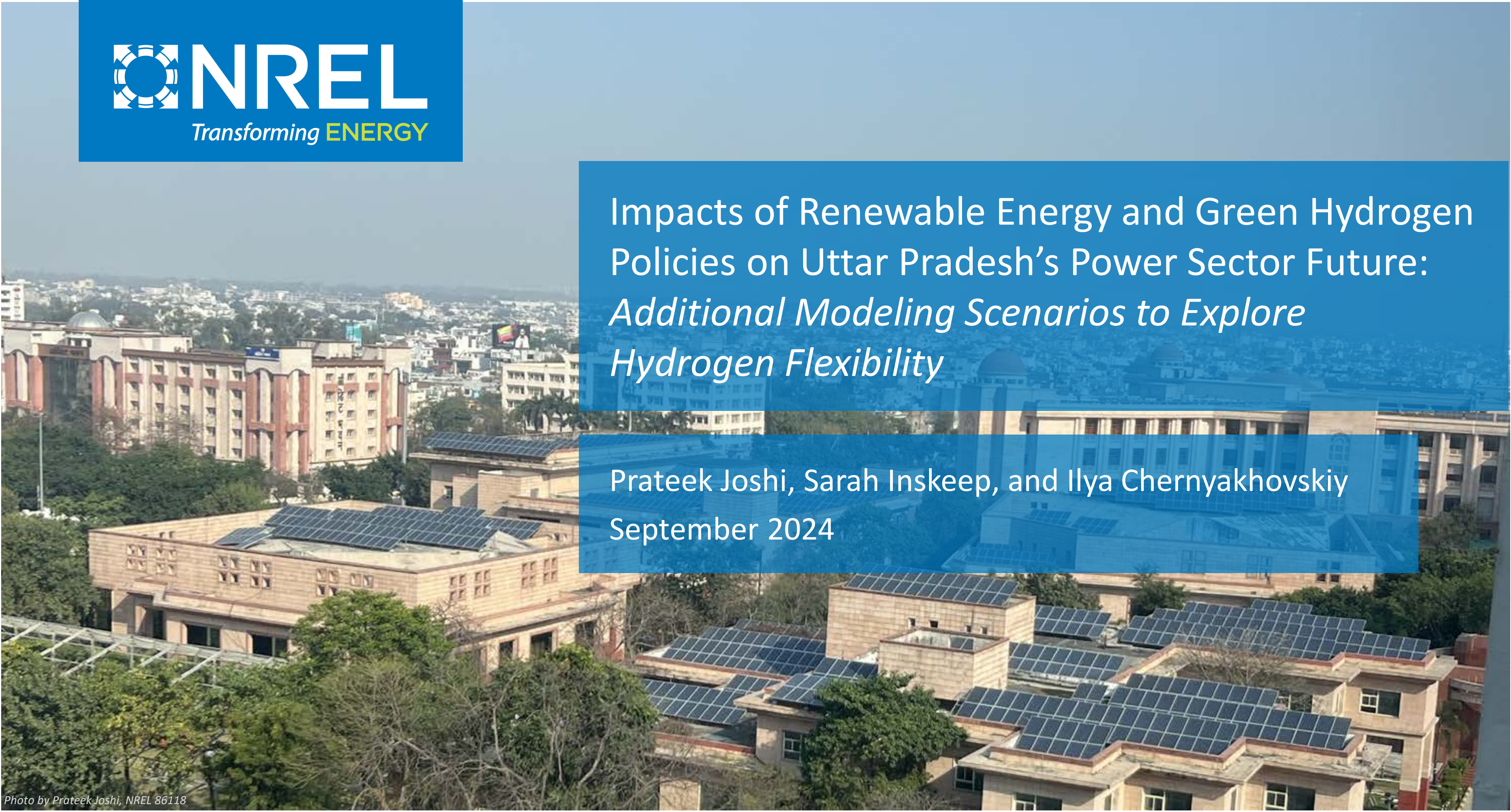

Photo by Prateek Joshi, NREL 86118

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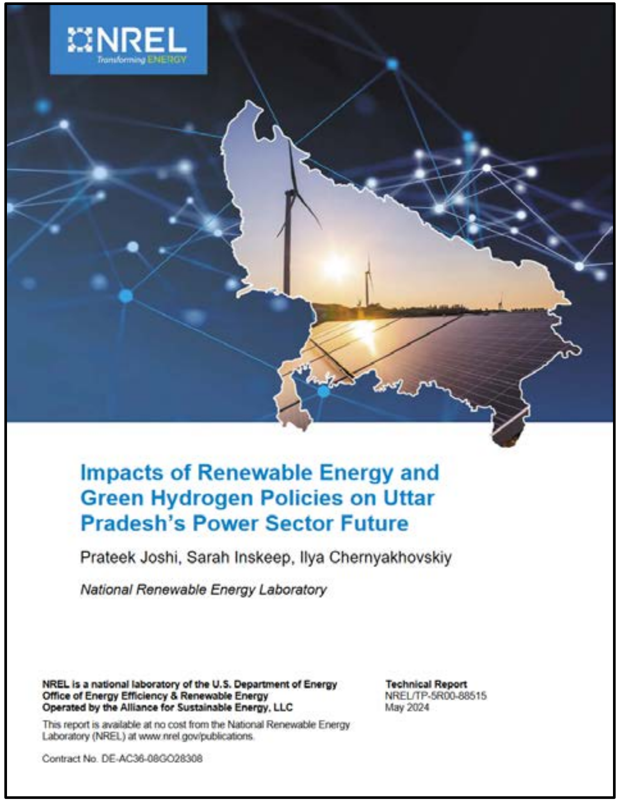


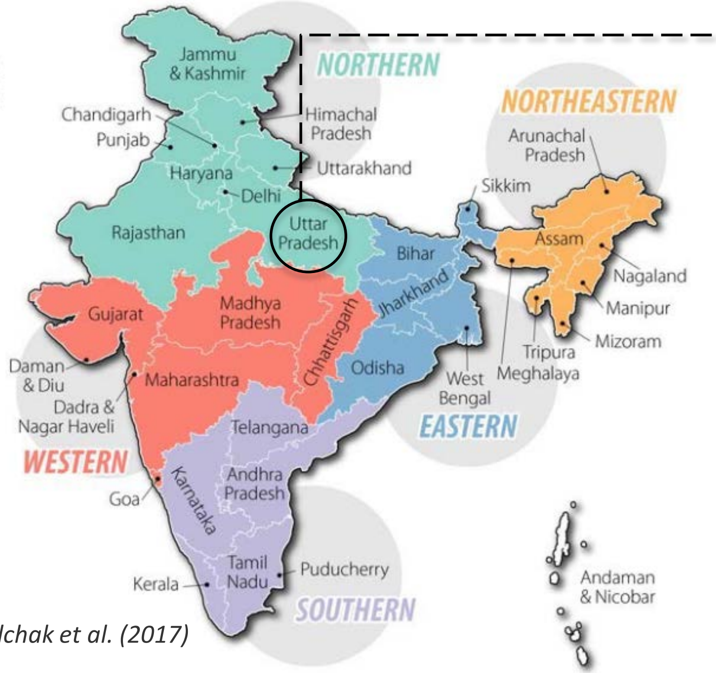
This slide deck builds off the core scenarios modeled in the original study "*Impacts of Renewable Energy and Green Hydrogen Policies on Uttar Pradesh's Power Sector Future*".

The methodology and assumptions for the Uttar Pradesh power sector model are documented in the original study.

The modeling tool used is Regional Energy Deployment System (ReEDS) India, an open-access tool for mid- and long-term capacity expansion modeling that finds the mix of generation, transmission, and storage technologies that meet the anticipated requirements of the electric sector at least cost.

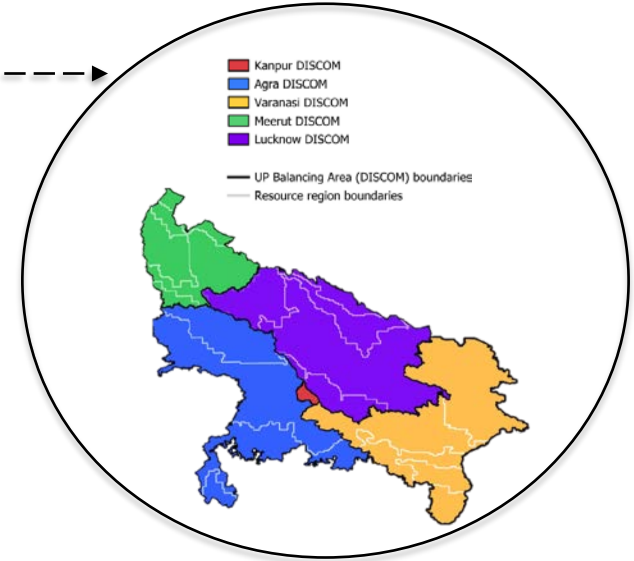
Power Sector Planning Model for Uttar Pradesh

Link to Original Study



Palchak et al. (2017)

The ReEDS-India model represents each Indian state and union territory as one balancing area within India's transmission network.



Uttar Pradesh is further subdivided into 5 balancing areas (corresponding to DISCOMs) and 21 resource regions.

Original Study Scenarios

Link to Original Study

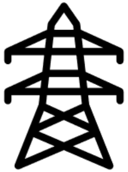
Scenario Name	Renewable Energy Policy Targets	Green Hydrogen Production	Electricity for Green Hydrogen Production
Reference	None	None	N/A
RE Policy	UPNEDA policies: pumped hydro (12 GW by 2028) and solar PV (22 GW by 2027) targets	None	N/A
RE Policy, Baseline Green H_2	UPNEDA policies: pumped hydro (12 GW by 2028) and solar PV (22 GW by 2027) targets	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 met by in-state or out-of-state renewables
RE Policy, Baseline Green H_2, Co-located RE[1]	UPNEDA policies: pumped hydro (12 GW by 2028) and solar PV (22 GW by 2027) targets	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 only be met by in-state co-located (i.e., in the same balancing area) renewables

Green Hydrogen Scenarios (RE Policy, Baseline Green H_2; RE Policy, Baseline Green H_2, Co-located RE)

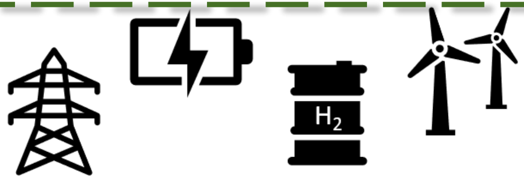
[1] This scenario was developed as a test case to determine the feasibility of using co-located renewables, without co-located long-duration electricity and/or hydrogen storage, to meet all of Uttar Pradesh's projected green hydrogen production needs.

Strategies to Meet Uttar Pradesh's Green Hydrogen Targets

Link to Full Report



Electricity Imports
(RE Policy, Baseline Green H_2)



Some combination of imports, co-located renewables, and potentially long-duration electricity and/or hydrogen storage

Co-Located Renewables
(RE Policy, Baseline Green H_2, Co-Located RE)

Electricity Imports

- ✓ Lower cost
- ✓ National renewable energy generation is sufficient
- X Less energy security
- X Lower in-state economic benefits (i.e., jobs, revenue, etc.)

Combination

- ↔ Ensure a balance between cost, energy security, and other state priorities

Co-Located Renewables

- ✓ More energy security
- ✓ Higher in-state economic benefits (i.e., jobs, revenue, etc.)
- X Higher cost
- X Very large and rapid buildout of wind

The focus of these additional modeling scenarios is to further examine the solution space in between the two simplified bookend strategies discussed in the original report (Electricity Imports and Co-Located Renewables) to meet Uttar Pradesh's green hydrogen targets, through additional modeling that combines both approaches and represents more spatial and temporal flexibility in green hydrogen production.

Green Hydrogen Scenarios

Updating the Green Hydrogen Scenarios to Reflect Uttar Pradesh's Approved Policy

	Scenario Name	Renewable Energy Policy Targets	Green Hydrogen Production	Electricity for Green Hydrogen Production
Original Study: assumptions based on UPNEDA's 2023 draft green hydrogen policy	RE Policy, Baseline Green H_2	UPNEDA policies: pumped hydro (12 GW by 2028) and solar PV (22 GW by 2027) targets	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 met by in-state or out-of-state renewables
	RE Policy, Baseline Green H_2, Co-located RE			Electricity for green hydrogen production can only be met by in-state co-located (i.e., in the same balancing area) renewables
Additional Scenarios: assumptions based on UPNEDA's 2024 approved green hydrogen policy	RE Policy, Baseline Green H_2		Baseline growth in green hydrogen production (**1.3 MMT and 62 TWh by 2030, 3.0 MMT and 143 TWh by 2050**)	Electricity for green hydrogen production can be met by in-state or out-of-state renewables
	RE Policy, Baseline Green H_2, Co-located RE			Electricity for green hydrogen production can only be met by in-state co-located (i.e., in the same balancing area) renewables

Impacts of the Approved Green Hydrogen Policy: RE Policy, Baseline Green H_2 Scenario

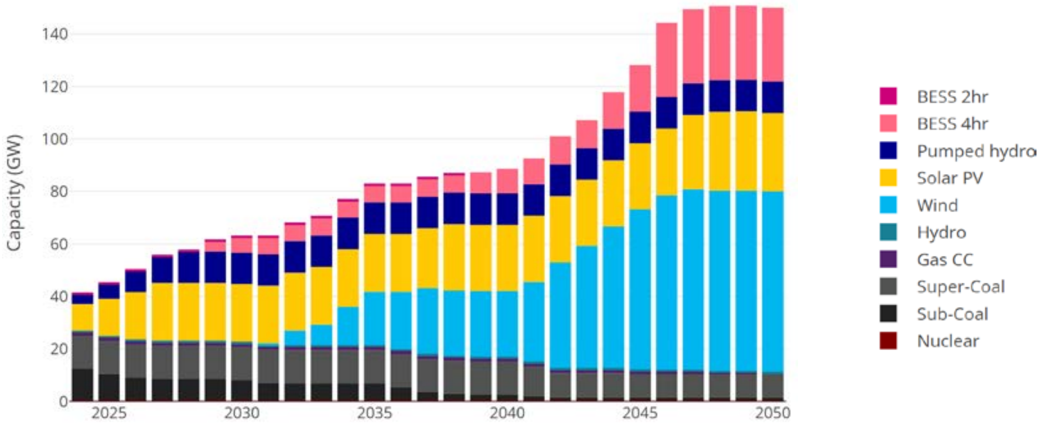


Figure. Uttar Pradesh Installed Capacity (2024-2050)

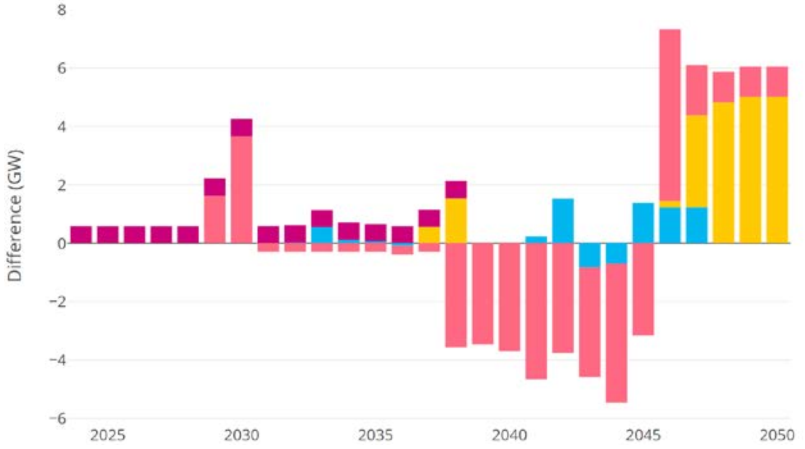


Figure. Difference in Uttar Pradesh Installed Capacity Using the 2024 Approved Policy Compared to the 2023 Draft Policy (2024-2050)

Year	Coal	Gas	Wind	Solar PV	Pumped Hydro	BESS
2030	20.3 GW (32%)	1.5 GW (2%)	0 GW (0%)	22 GW (35%)	12 GW (19%)	6.4 GW (10%)
2050	10.4 GW (7%)	0 GW (0%)	68.7 GW (46%)	29.8 GW (20%)	12 GW (8%)	28.3 GW (19%)

Results show that 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 when accounting for the 2024 approved policy compared to the 2023 draft policy.

Impacts of the Approved Green Hydrogen Policy: RE Policy, Baseline Green H_2, Co-Located RE Scenario

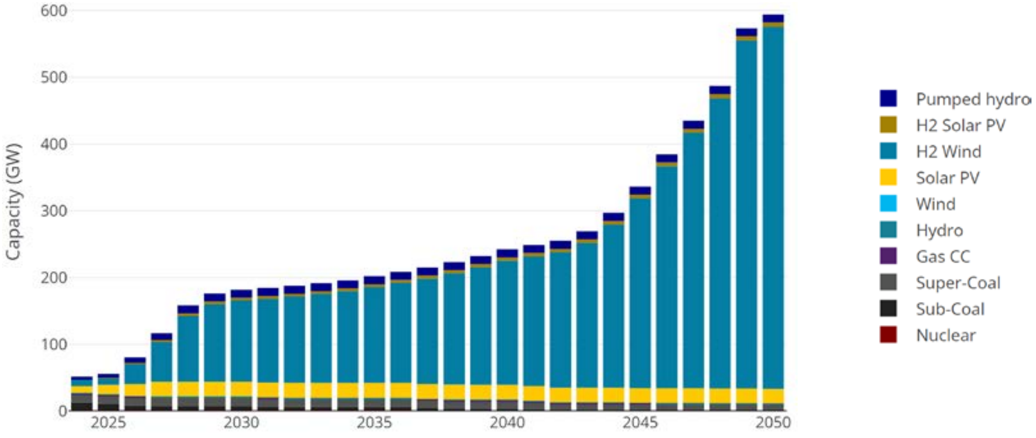


Figure. Uttar Pradesh Installed Capacity (2024-2050)

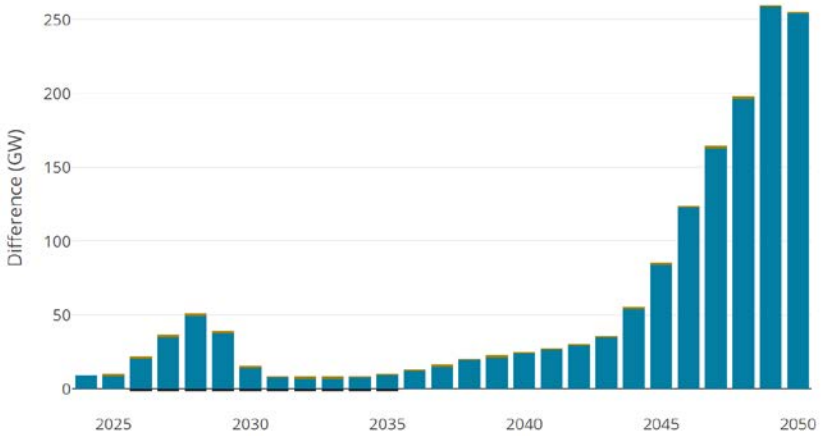


Figure. Difference in Uttar Pradesh Installed Capacity Using the 2024 Approved Policy Compared to the 2023 Draft Policy (2024-2050)

Year	Coal	Gas	Wind*	Solar PV*	Pumped Hydro	BESS
2030	19.1 GW (11%)	1.5 GW (1%)	122.6 GW (67%)	22 GW (12%)	12 GW (7%)	0 GW (0%)
2050	10.4 GW (2%)	0 GW (0%)	543.1 GW (91%)	27.9 GW (5%)	12 GW (2%)	0 GW (0%)

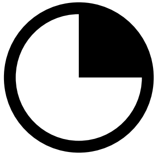
*Wind and Solar PV includes “H_2 Wind” and “H_2 Solar PV” respectively, referring to co-located wind and solar PV used to generate green hydrogen

Results show that there is an increase of 49.7 GW of H_2 Wind (31% of total capacity) in 2028, an increase of 14.4 GW of H_2 Wind (8% of total capacity) in 2030, an increase of 24.1 GW of H_2 Wind (10% of total capacity) in 2040, and an increase of 254.4 GW of H_2 Wind (43% of total capacity) in 2050 when accounting for the 2024 approved policy compared to the 2023 draft policy.

Sensitivities to Further Examine the Need for Co-Located Renewables to Meet Green Hydrogen Targets

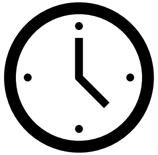
Scenario Name	Renewable Energy Policy Targets	Green Hydrogen Production	Electricity for Green Hydrogen Production
RE Policy, Baseline Green H_2, Co-located RE	UPNEDA policies: pumped hydro (12 GW by 2028) and solar PV (22 GW by 2027) targets	Baseline growth in green hydrogen production (1.3 MMT and 62 TWh by 2030, 3.0 MMT and 143 TWh by 2050)	Electricity for green hydrogen production can only be met by in-state co-located (i.e., in the same balancing area) renewables

Sensitivity A:
Combination of Imports and Co-Located Renewables



Sensitivity B:
Spatial Flexibility of Green Hydrogen Production

Sensitivity C:
Temporal Flexibility of Green Hydrogen Production



Because the rapid and large buildout of wind in the "RE Policy, Baseline Green H_2, Co-located RE" scenario was not considered feasible by stakeholders in Uttar Pradesh, additional sensitivities were examined for this scenario to gauge the impact on the state's capacity mix.

Sensitivity A:
Combination of Imports and Co-Located Renewables

Sensitivity A: Combination of Imports and Co-Located Renewables

Scenario:

RE Policy, Baseline Green H_2, Co-located RE

- **100%** of the electricity demand for green hydrogen production must be met by in-state co-located (i.e., in the same balancing area) renewables

Sensitivity A:

Combination of Imports and Co-Located Renewables

- **25%, 50%, or 75%** of the electricity demand for green hydrogen production must be met by in-state co-located (i.e., in the same balancing area) renewables

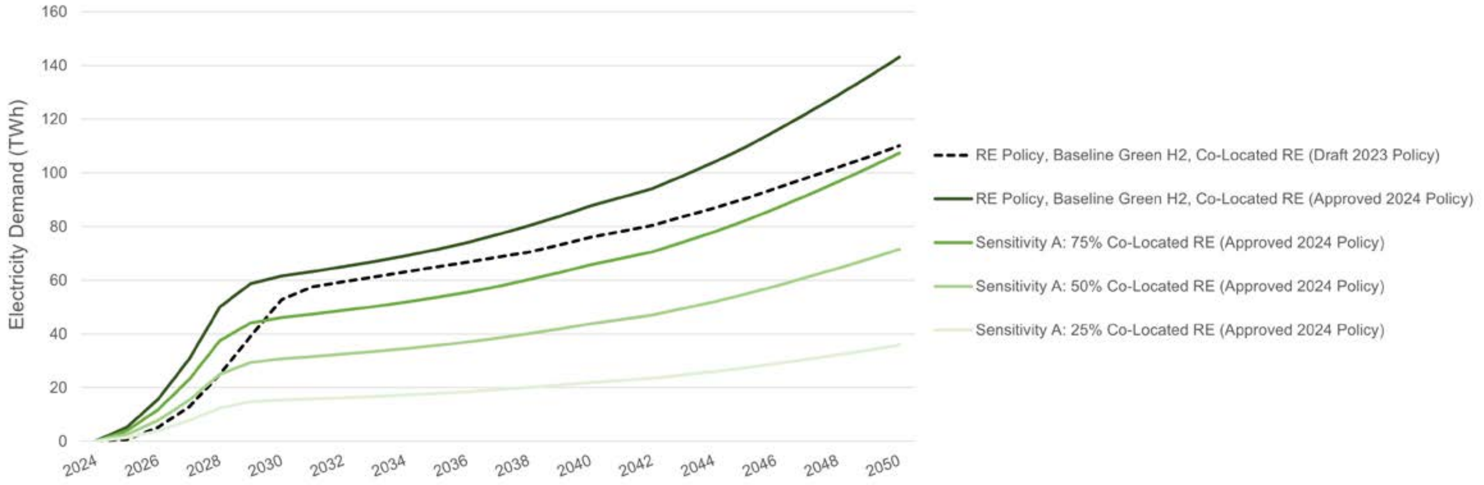


Figure. Electricity Demand for Green Hydrogen Production by Scenario and Sensitivity

Sensitivity A: 2030 Results

- Through 2030, adjusting the allocations (25%, 50%, 75%, and 100%) of electricity demand for green hydrogen production met by co-located renewables impacts total imports from or exports to the grid, as well as buildouts of co-located solar PV and wind (H_2 Solar PV and H_2 Wind) in the Uttar Pradesh DISCOMs.

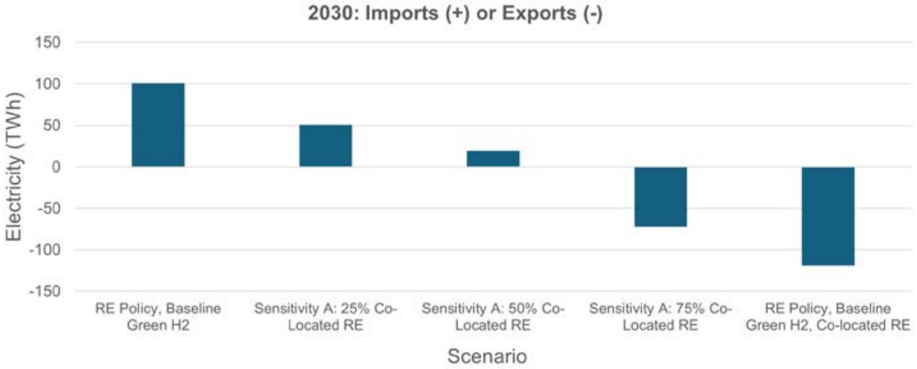


Figure. Uttar Pradesh Net Electricity Imports or Exports by Scenario

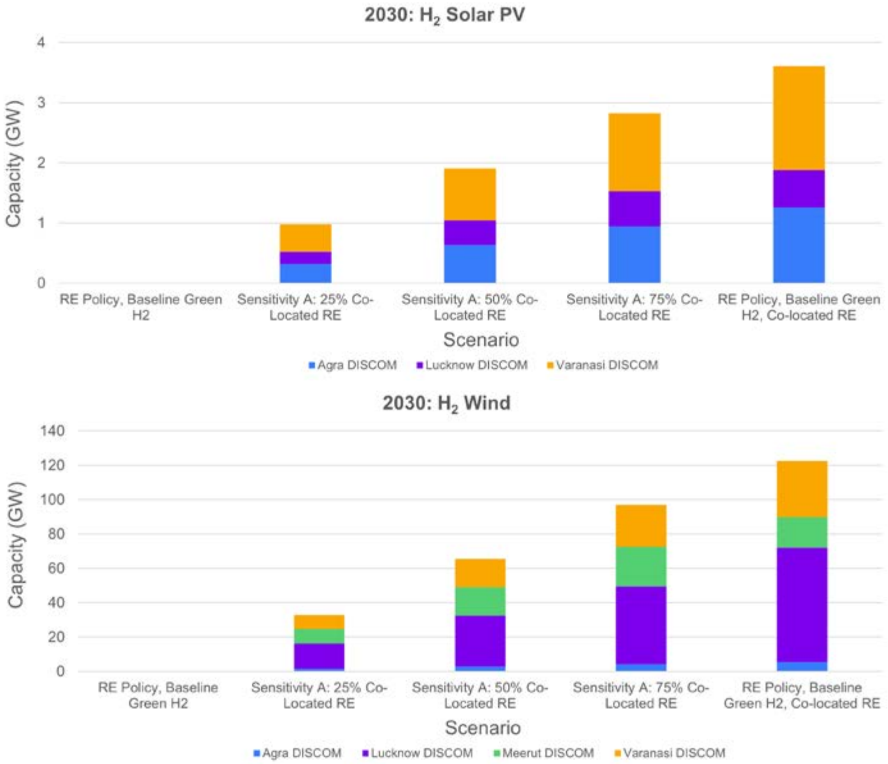


Figure. Uttar Pradesh Installed Capacity of Co-Located RE by DISCOM and Scenario

Sensitivity A: 2050 Results

- By 2050, regular (non co-located) wind buildouts in the Meerut DISCOM and regular (non co-located) solar PV buildouts in the Varanasi DISCOM are displaced by buildouts of co-located solar PV and wind (H_2 Solar PV and H_2 Wind).
- Compared to the "RE Policy, Baseline Green H_2, Co-Located RE Scenario", costs decline by 30%, 46%, and 58% for the 75% Co-Located RE, 50% Co-Located RE, and 25% Co-Located RE sensitivities, respectively.[1]

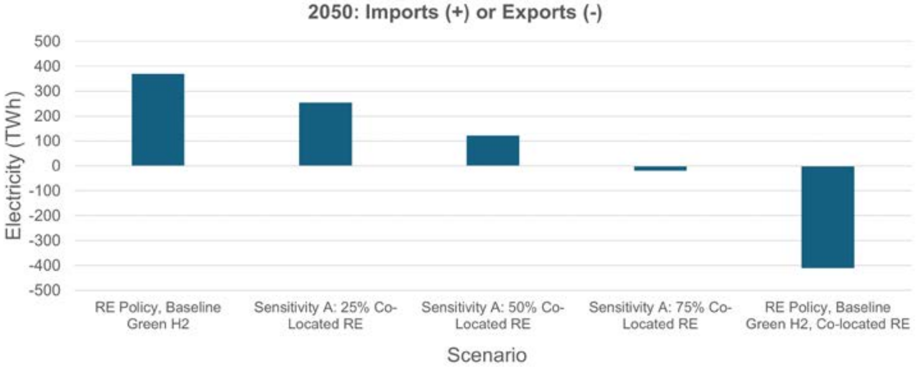


Figure. Uttar Pradesh Net Electricity Imports or Exports by Scenario

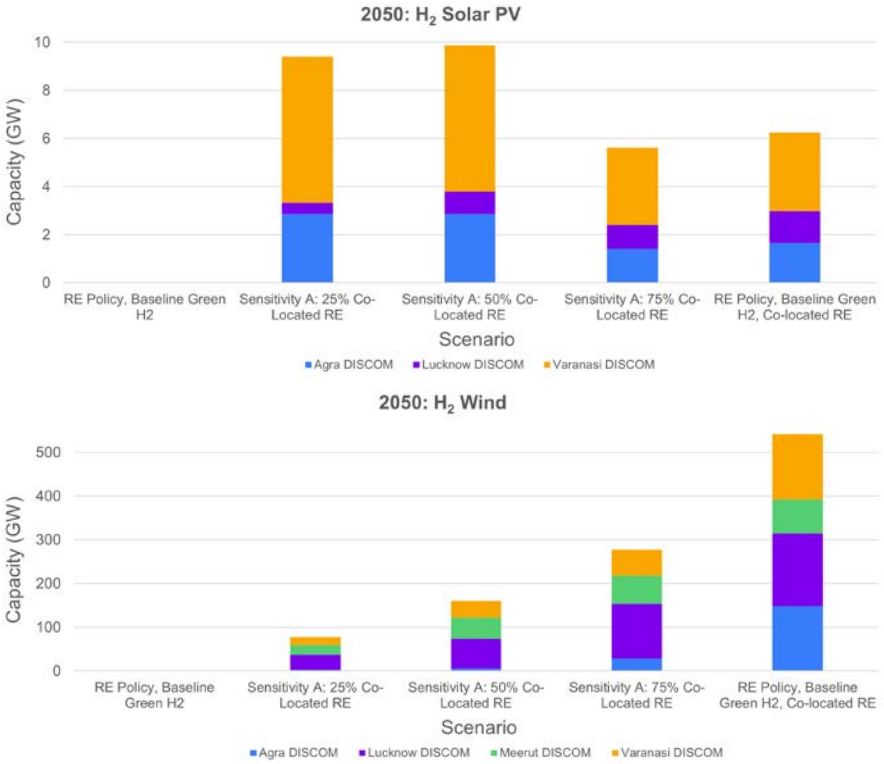


Figure. Uttar Pradesh Installed Capacity of Co-Located RE by DISCOM and Scenario

[1] 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.

Sensitivity B:
Spatial Flexibility of Green Hydrogen Production

Sensitivity B: Spatial Flexibility of Green Hydrogen Production

Scenario:

RE Policy, Baseline Green H_2, Co-located RE

- ➢ The proportion of electricity demand for green hydrogen production is allocated to DISCOMs based on the locations of existing and anticipated fertilizer plants and refineries.

Sensitivity B:

Spatial Flexibility of Green Hydrogen Production

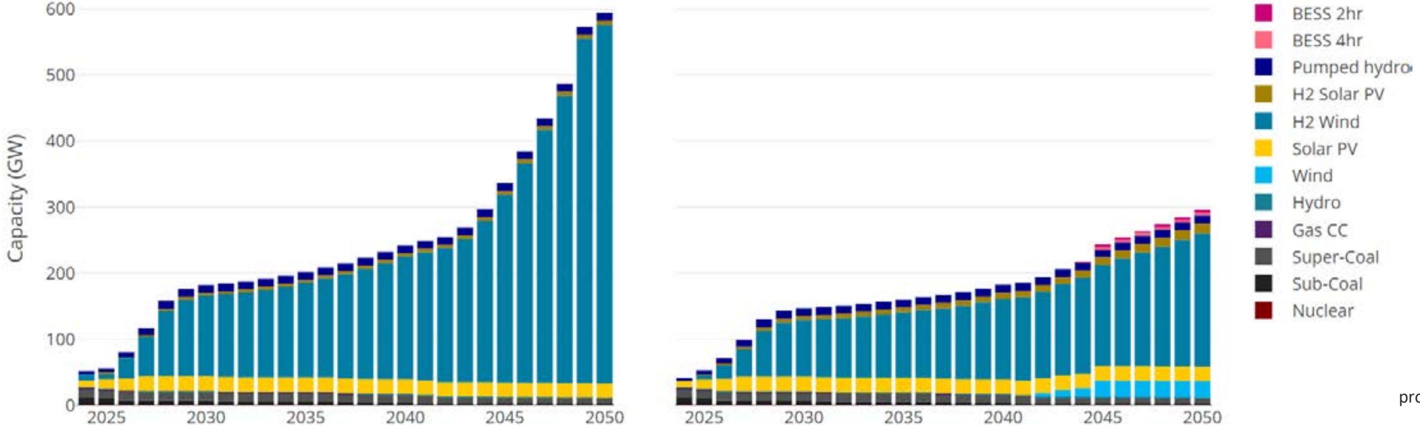
- ➢ The proportion of electricity demand for green hydrogen production is allocated to DISCOMs based on the quality of renewable energy resources (represented by combined average wind and solar PV capacity factors).

The proportion of electricity demand for green hydrogen production assigned to each DISCOM remains constant each year.

Figure. Proportion of Electricity Demand for Green Hydrogen Production by DISCOM in the RE Policy, Baseline Green H_2, Co-Located RE Scenario (i) and Sensitivity B (ii)

Sensitivity B: Results

- Allocating green hydrogen demand to DISCOMs based on wind and solar resources decreases the total installed capacity in Uttar Pradesh by 24% in 2030 and by 59% in 2050. The state exports ~50 TWh of electricity in 2030, and imports ~100 TWh of electricity (~15% of total demand) in 2050.
- By 2050, this spatial balancing of green hydrogen demand also leads to increases in BESS (~7 GW), solar PV that is co-located with hydrogen production (~9 GW), and wind that is not co-located with hydrogen production (~25 GW).
- Spatial flexibility of green hydrogen production reduces total system costs for Uttar Pradesh by 39% from 2020-2050.[2]



(i) (ii)

[2] 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. Uttar Pradesh Installed Capacity in the RE Policy, Baseline Green H_2, Co-located RE Scenario (i) Compared to the Spatial Flexibility of Green Hydrogen Production Sensitivity (ii) from 2024-2050

Sensitivity C:
Temporal Flexibility of Green Hydrogen Production

Sensitivity C: Temporal Flexibility of Green Hydrogen Production

Scenario:

RE Policy, Baseline Green H_2, Co-located RE

- ➢ The total annual electricity demand for green hydrogen production is divided across each hour of the year evenly.
- ➢ Assumes constant electrolyzer operation.

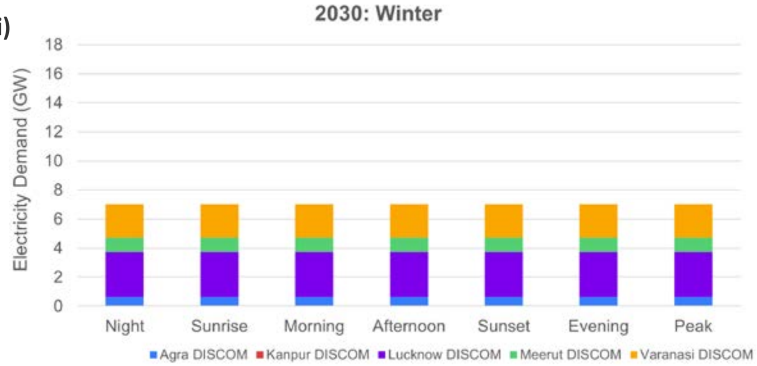
Sensitivity C:

Temporal Flexibility of Green Hydrogen Production

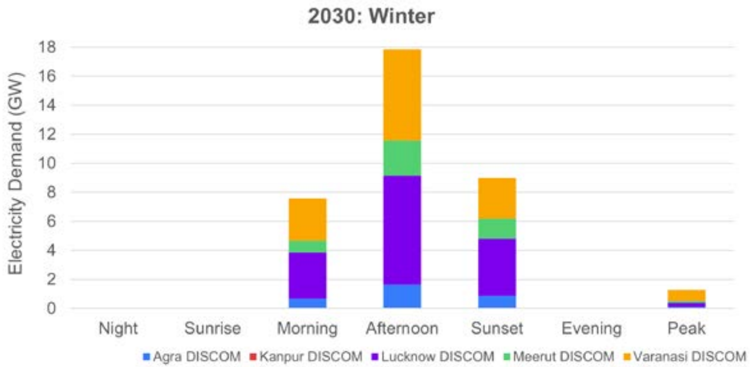
- ➢ The total annual electricity demand for green hydrogen production is divided across each hour of the year based on renewable energy generation (i.e., hours with more wind and solar PV generation are assigned higher green hydrogen demand).
- ➢ Assumes variable electrolyzer operation.

Figure. Electricity Demand for Green Hydrogen Production by DISCOM and Time Slice in the RE Policy, Baseline Green H_2, Co-Located RE Scenario (i) and Sensitivity C (ii)

(i)



(ii)



Sensitivity C: Results

- Allocating green hydrogen demand to times of day with higher wind and solar generation decreases the total installed capacity in Uttar Pradesh by 49% in 2030 and by 73% in 2050. In-state resources still meet total demand in 2030, though imports of ~200 TWh of electricity (~30% total demand) are needed in 2050.
- H_2 Solar PV becomes the primary co-located renewable energy technology to meet electricity demand for green hydrogen production, augmented by much smaller amounts of H_2 Wind.
- Temporal flexibility of green hydrogen production reduces total system costs for Uttar Pradesh by 55% from 2020-2050.[3]

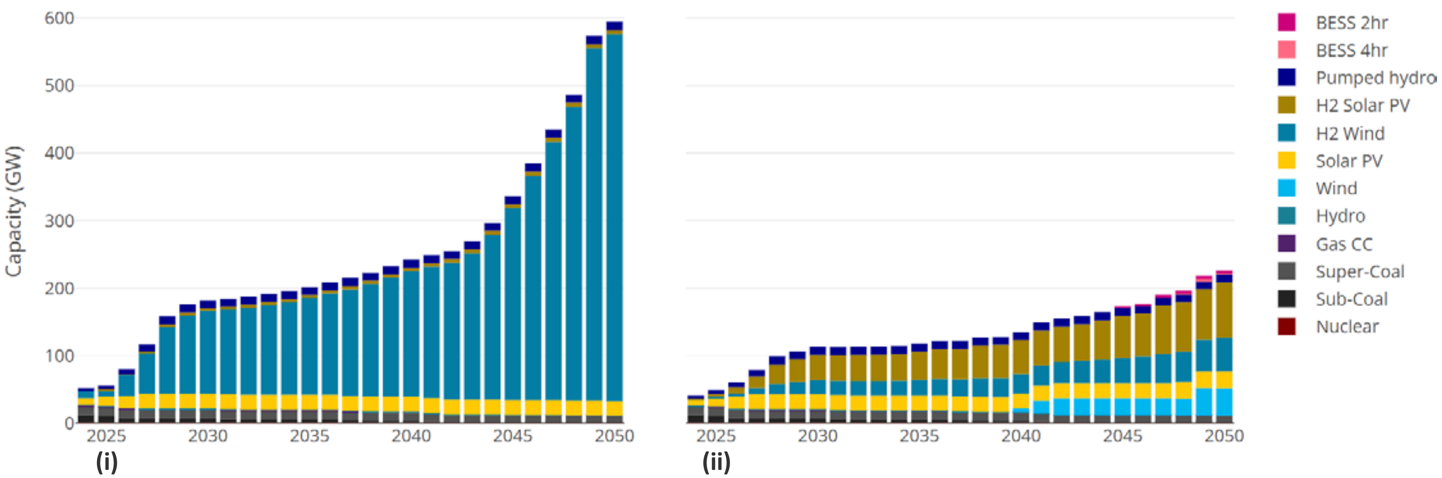


Figure. Uttar Pradesh Installed Capacity in the RE Policy, Baseline Green H_2, Co-located RE Scenario (i) Compared to the Temporal Flexibility of Hydrogen Production Sensitivity (ii) from 2024-2050

Sensitivity C: Installed Capacity of Renewables & BESS

2030 Capacity:
- Solar PV: 22 GW
- H_2 Solar PV: 37 GW
- H_2 Wind: 21 GW

2050 Capacity:
- Solar PV: 25 GW
- H_2 Solar PV: 82 GW
- Wind: 40 GW
- H_2 Wind: 50 GW
- BESS 2hr: 2 GW

[3] 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.

Key Takeaways

Key Takeaways

[4] 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.

When going from meeting 50% of electricity demand for green hydrogen production with co-located renewables to meeting 75%, Uttar Pradesh transitions from a net electricity importer to a net electricity exporter in both 2030 and 2050 (without spatial or temporal flexibility sensitivities).

A more balanced distribution of green hydrogen demand among the larger Uttar Pradesh DISCOMs (i.e., excluding the Kanpur DISCOM) reduces the total installed capacity (59% decrease) and the total system costs (39% decrease) required to meet 100% of electricity demand for green hydrogen production with co-located renewables by 2050.[4]

Shifting green hydrogen demand to times of the day with higher combined wind and solar resources (i.e., in the middle of the day) reduces the total installed capacity (73% decrease) and the total system costs (55% decrease) required to meet 100% of electricity demand for green hydrogen production with co-located renewables by 2050.[4]

A portfolio of strategies (i.e., a combination of imports and co-located renewables, paired with spatial and temporal flexibility of green hydrogen production) can help Uttar Pradesh reliably and cost-effectively meet the goals outlined in its 2024 approved green hydrogen policy.

References

Joshi, Prateek, Sarah Inskeep, and Ilya Chernyakhovskiy. "Impacts of Renewable Energy and Green Hydrogen Policies on Uttar Pradesh's Power Sector Future." Technical Report. Golden, CO: National Renewable Energy Laboratory (NREL), May 2024. http://www.nrel.gov/docs/fy24osti/88515.pdf.

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Acronyms

BESS: battery energy storage system
CC: combined cycle
DISCOM: distribution company
H_2: hydrogen
MMT: million metric tons
NREL: National Renewable Energy Laboratory
PV: photovoltaic
RE: renewable energy
ReEDS: Regional Energy Deployment System
UPNEDA: Uttar Pradesh New and Renewable Energy Development Agency

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