Flexible Resources Initiative of the U.S.-India Clean Energy Finance Task Force

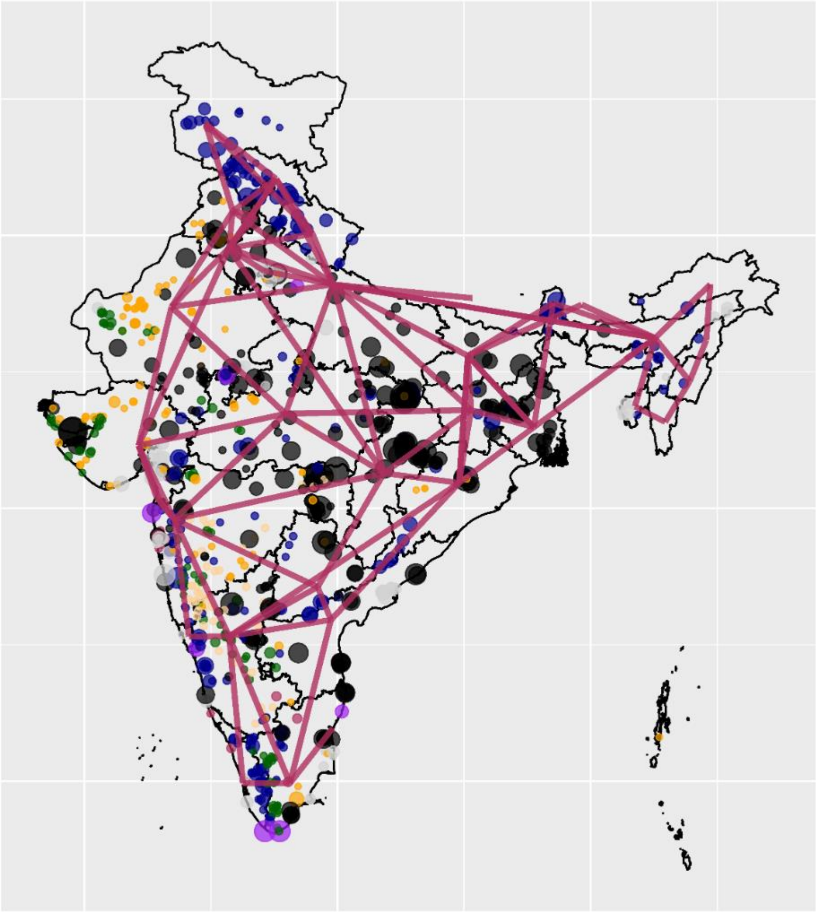
Least-Cost Pathway for India's Power System Investments through 2030

Dr. Nikit Abhyankar
Shruti Deorah
Dr. Amol Phadke
Lawrence Berkeley National Laboratory

December 2021

Summary

- **What did we do ?**
  - Assess a least-cost resource mix for the Indian power sector up to 2030
  - Comprehensive system expansion and hourly operational modeling at individual power plant level
  - Identify concrete policy / regulatory solutions



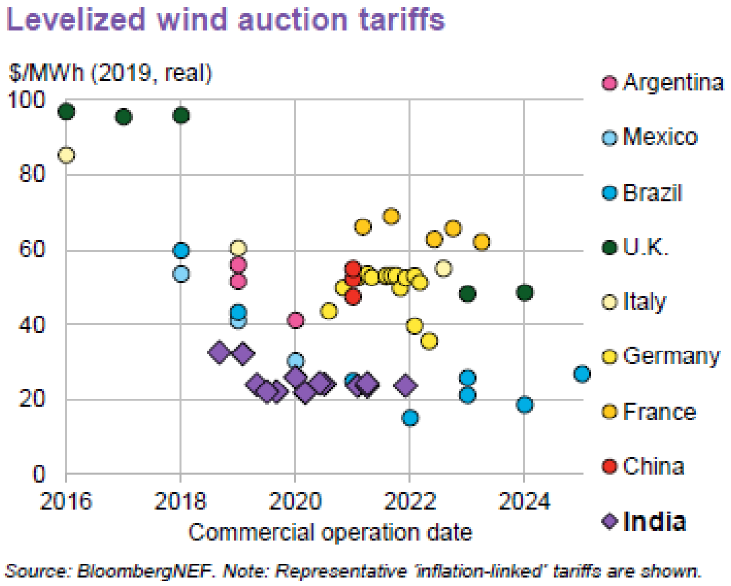
- **What did we find ?**
  - The least cost pathway by 2030 includes 464 GW of RE + flexible resources: 63GW (252 GWh) energy storage, 60GW load shifting, flex operation of 25 GW gas, >140GW new interstate transmission, & national wholesale electricity markets
  - 23 GW of net addition to the coal capacity by 2030 (may be higher in case RE/storage costs do not drop or deployment barriers)
  - Average electricity price reduces by 8-10% between 2020 and 2030
  - CO_2 emissions intensity of power generation reduces by 43-50% from 2020 level
  - Unlikely to lead to job losses in the coal sector in near to medium term
  - Need significant policy / regulatory interventions (resource adequacy framework, storage regulations, capacity markets, wider/deeper energy markets)

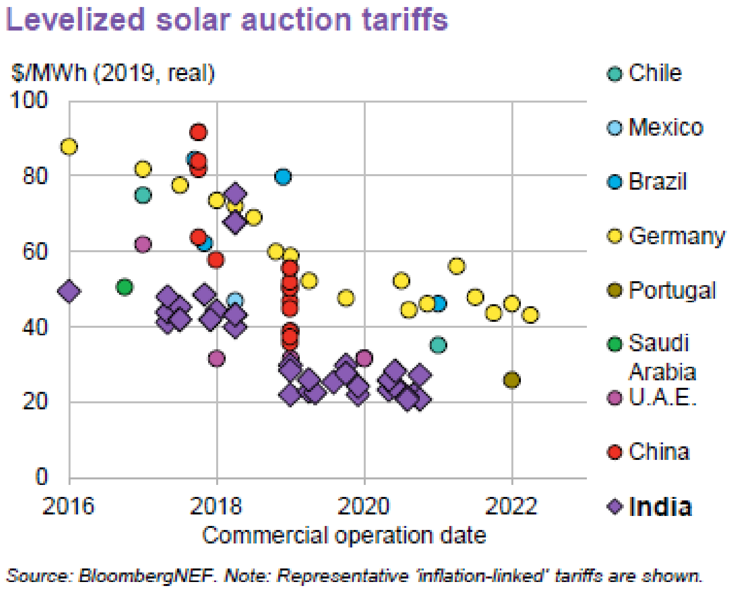
- **What are the implications ?**
  - A least-cost pathway to achieving PM Modi's 500GW clean energy target at COP-26

Solar & wind are the cheapest resources in India while the country needs to double its electricity infrastructure in the next 10-15 years

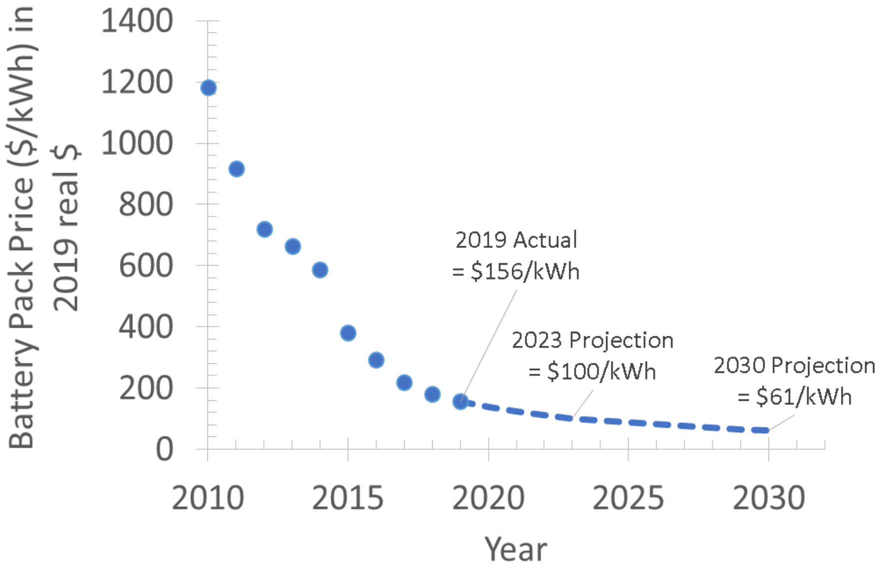
- India has achieved some of the lowest solar and wind prices in the world.
- Solar LCOE has reduced by 85% in the last 10 years
- Solar PPA prices in 2020-21: ~Rs 2/kWh, which is lower than the variable cost of ~100 GW of existing coal assets

- Battery prices have dropped by ~90% in the last 10 yrs
- In FY 2022, battery storage capital cost (global avg) is ~Rs 6.5 Cr/MW (4-hour)





Source: BNEF (2020)



Source: BNEF (2020)

➔ By 2025-2030 Solar + 30% battery storage would cost ~Rs 3.0-3.5/kWh, nominally flat for 20 yrs.

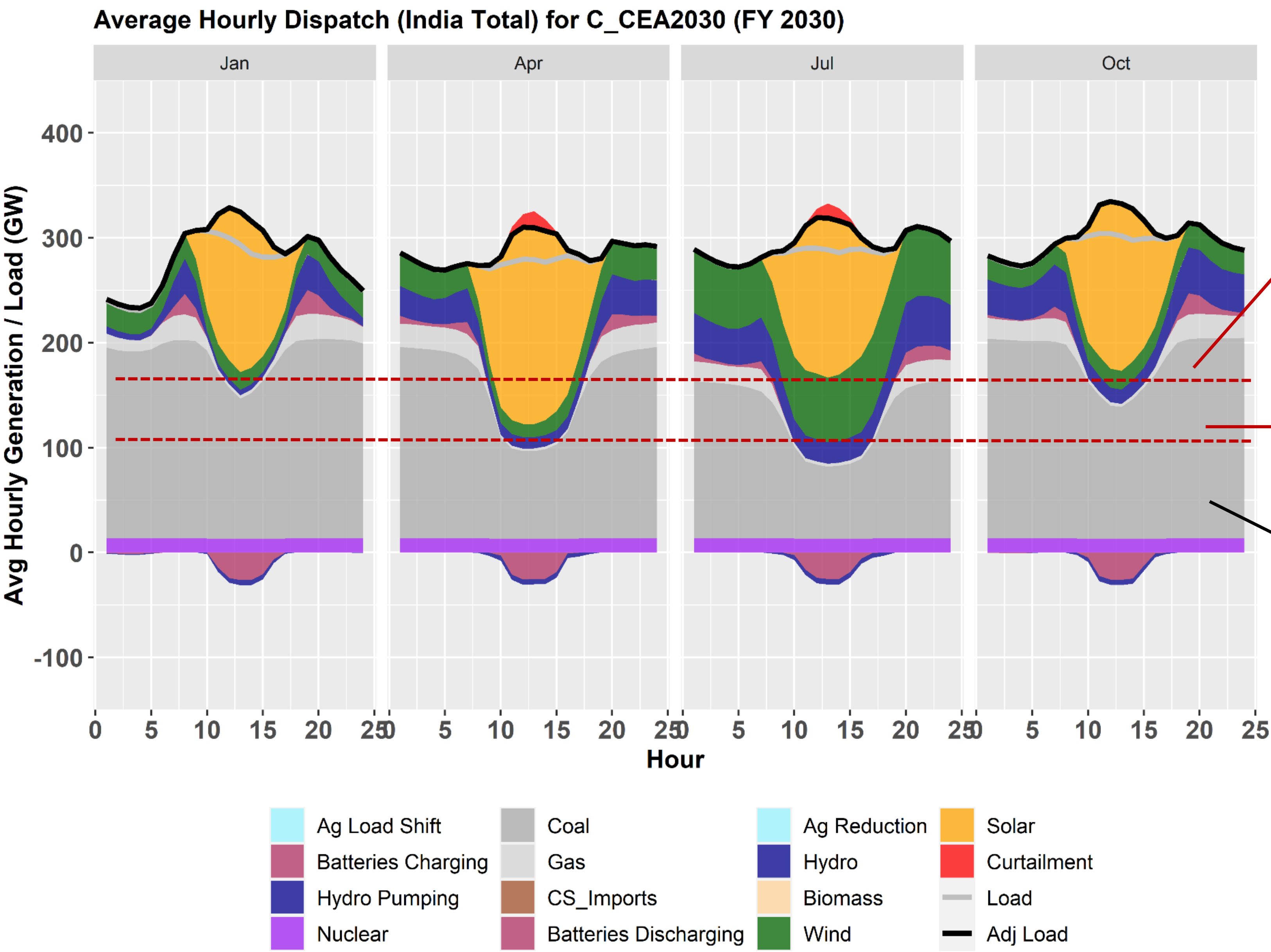
Flexible Resources Initiative (FRI) National Study Overview

- Context and Objective
  - Current events and recent declines in RE and battery costs and gas prices, and electricity market reforms offer a unique opportunity to India to leapfrog to a more flexible, robust, and sustainable power system, in view of unexpected challenges and disruptions.
  - LBNL assesses a least cost resource mix for India with a focus on key flexible resources ("FRs," e.g. energy storage like batteries / pumped hydro, gas, load shifting, hydro, and electricity markets) to support India's energy transition over the next decade

- PLEXOS, an industry standard tool, is used to:
  - Model optimal capacity expansion at the state level through 2030 and simulate hourly dispatch at the power plant level in 2030, over a range of scenarios on RE costs, gas prices, coal retirements, demand growth, electricity markets, supply chain challenges, etc.

- Key Findings
  - The least cost pathway up to 2030 consists of a combination of RE (~350-450 GW_{DC}) + FRs: 30-60GW energy storage, 60GW load shifting, flexible operation of 25 GW gas, >140GW of additional interstate/inter-regional transmission, and market-based economic dispatch (MBED)
  - 23 GW of net addition to the coal capacity is cost-effective by 2030 (may be higher in case RE/storage costs do not drop or deployment barriers)
  - The complementarity of FRs working in tandem is crucial for maintaining grid dependability in view of high RE penetration
  - Study outcomes point to some key policy and regulatory strategies on resource adequacy

RE + Coal expansion will cause significant stress on thermal assets



- Chart shows average hourly dispatch in FY 2030 for capacity mix per CEA Optimal Capacity Expansion Report
  (435GW RE + 37GW storage + 266GW Coal)
- ~50GW of coal capacity (existing / inefficient) will operate at <20-30% capacity factor
  ➔ **Avg cost of generation = Rs 7-8/kWh (Potentially stressed)**
- ~50 GW of coal capacity (mostly existing) will operate at ~40-50% capacity factor
  ➔ **Avg cost of generation = Rs 5-6/kWh (Potentially stressed)**
- ~160 of coal capacity (mostly new / efficient) will operate at ~70-80% capacity factor
  ➔ Avg cost of generation = ~Rs 3-3.5/kWh
- If coal and RE are both expanded aggressively, both sectors worse off:
  - **Financial** (low capacity factor) and **technical** (ramping / cycling) **stress** on coal assets
  - High RE curtailment
  - Both leading to higher system costs

Range of scenarios (30) are simulated to assess a Least-Cost Pathway

Main Scenarios for Optimal Capacity Expansion

RE + Batteries Cost • Low • Base • High (w/ supply chain constraints)	**Load Flexibility** • Ag Load shifted to solar hours • No load shifting
Future LNG Prices* • Base (LNG price (2030)= $5.5/MMBTU) • Low (LNG price (2030)= $4.5/MMBTU)	**Balancing** • State level • MBED (CERC staff paper)

* (including international shipping)

Sensitivity Cases

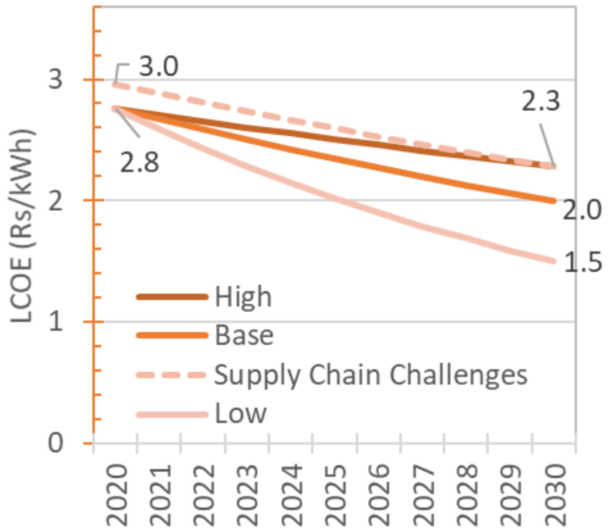
- Low Demand Growth (Peak Load by 2030 = 290GW)
- Coal power plants marked for retirement in the National Electricity Plan do not retire (~25GW)
- Start the optimization in FY 2021 (instead of FY2023)
- Supply chain challenges for solar and batteries

Detailed results for all scenarios and sensitivity cases are found at: https://public.tableau.com/profile/nikit.abhyankar#!/vizhome/FRICapExPrelimResultsv2/Story1

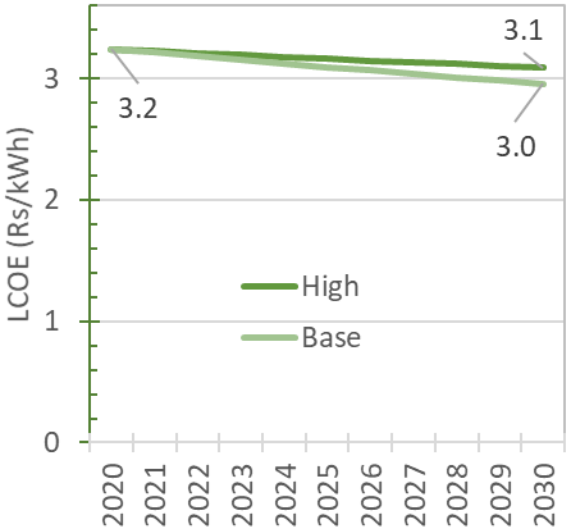
Key Assumptions

New technologies LCOE

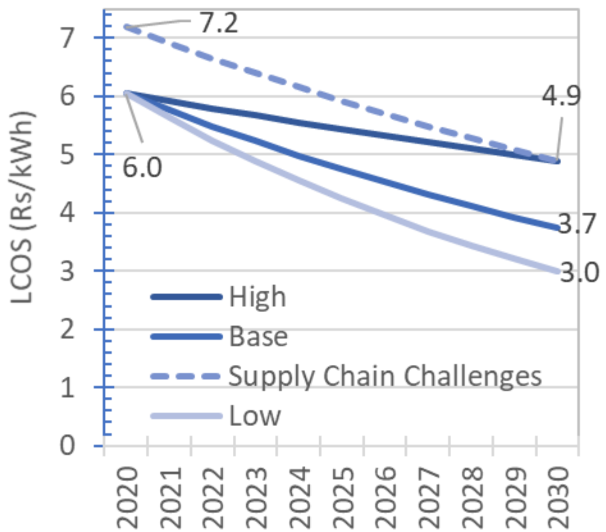
Solar



Wind



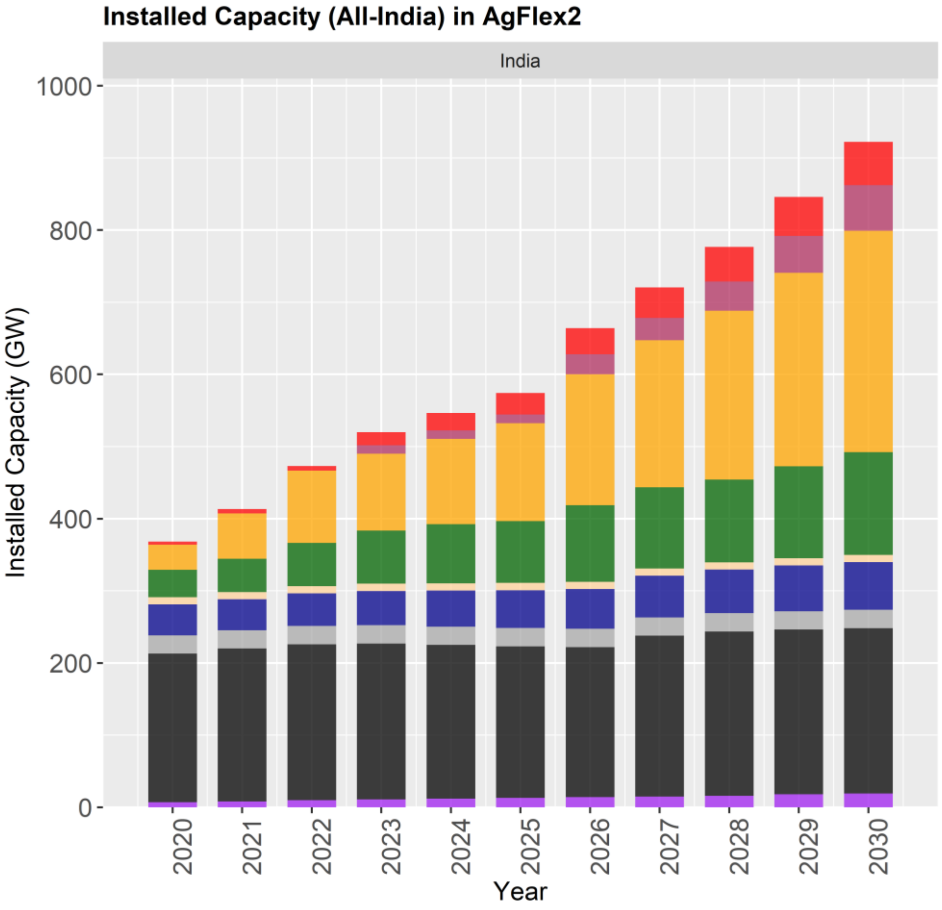
Battery Storage



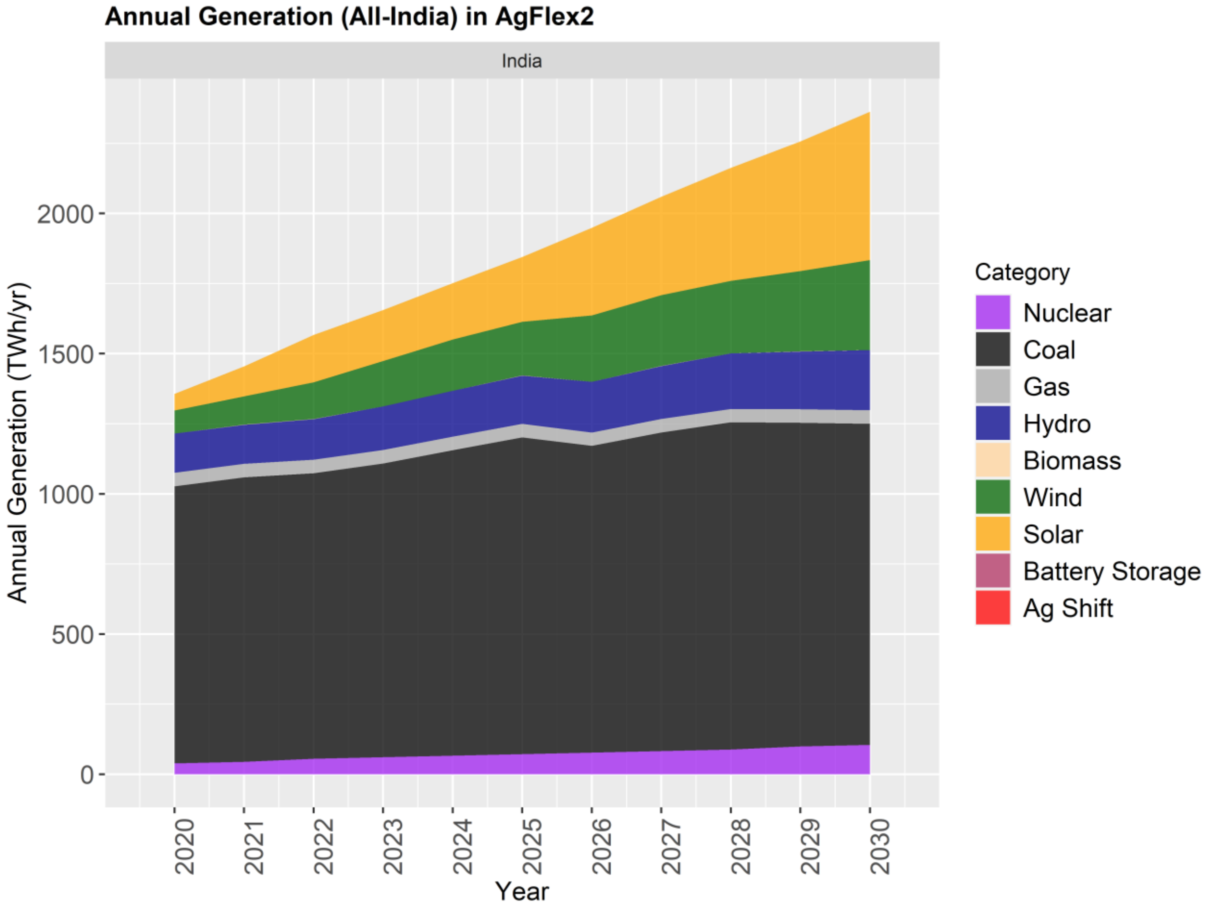
Capacity under construction	~38 GW of Coal capacity under construction (2020-2027) is included in the model; ~25GW of old coal capacity is assumed to be retired by 2027.	
Fuel Costs	Coal variable cost (pithead) for new plants LNG price	= Rs 1.6 – 2.1/kWh (2020), increasing at 1% p.a. = $4.5/MMBTU (Low) - $5.5/MMBTU (Base) (2030)
Load	Peak Load (2030) Load Shifting Potential (2030)	= 290 GW (Low) - 340 GW (Base) = ~50GW of Ag Load + ~10GW of Heavy Industry/Other Sectors
Transmission	Transmission Line Expansion cost	= Rs 10,162/MW-km (~$220/MW-mile)
Reserve Margin	Planning Reserve Margin	= 5% by FY 2030 (on top of ~8% auxiliary consumption + ~10-15% outages)

Nuclear and Hydro capacity expansion is not optimized; taken from the CEA Optimal Mix Report

The Primary Least Cost Pathway

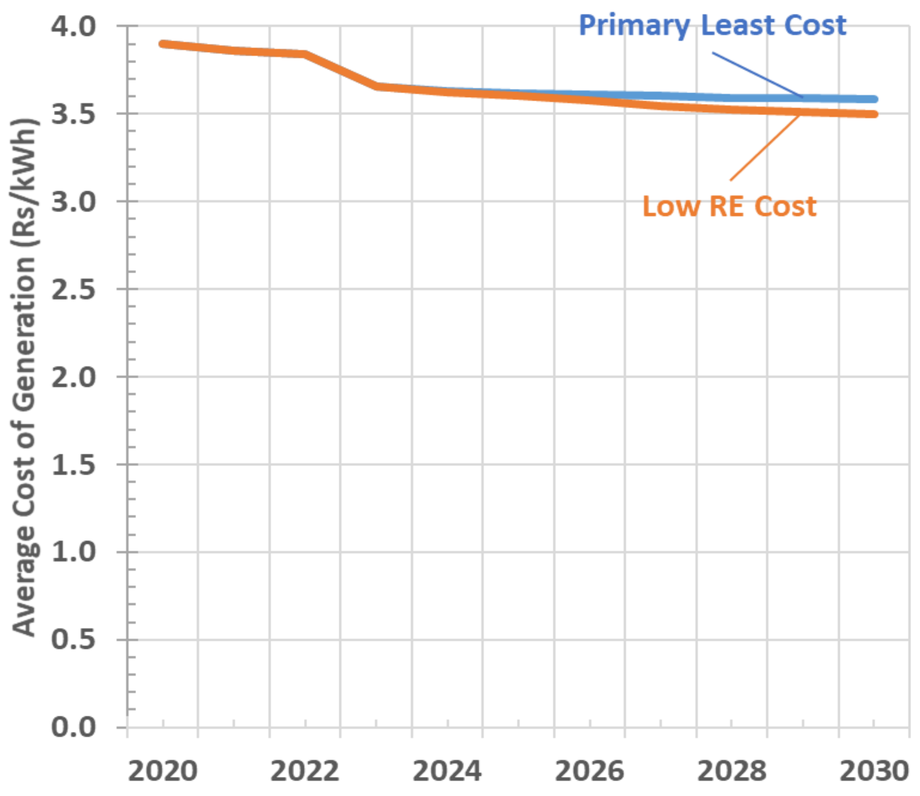


- Ag Load = ***Shifted***
- RE Cost = ***Base***
- Gas Price= ***Base***
- Balancing = ***State***
- Demand = ***Base***
- Supply Chain Challenges = ***No***
- 25GW planned coal retirements
- Optimization start year = ***FY 2023***



- We find the least cost mix by 2030 to be as follows:
- 307GW_{DC} solar + 142GW wind + 15 GW other RE (~464 GW Total)
- 63GW (252 GWh) of energy storage (~10% average daily RE generation)
- ~229 GW of coal + ~25 GW of gas
- ~140 GW of additional transfer capacity on interstate and inter-regional corridors
- Average Cost of Generation (FY 2030) = Rs 3.59/kWh, which is 10% lower than the 2020 cost.

Primary Least Cost pathway would reduce electricity costs by 8% from 2020 levels



- The average cost of electricity generation decreases by 8% from 2020 levels (Primary Least Cost case).
- If RE and storage prices decline faster - in line with the recent global trends - the average cost of generation drops by 10% (Low RE Cost case).

- ***Why?***
  - New solar / wind PPA prices would be lower than even the marginal cost of several coal power plants
  - Solar / wind /storage PPA prices are fixed in nominal terms making a huge portion of power procurement inflation proof.

Is the grid dependable ? (e.g. Primary Least Cost Pathway)

National Dispatch During Net Load Peak Week (FY 2030)

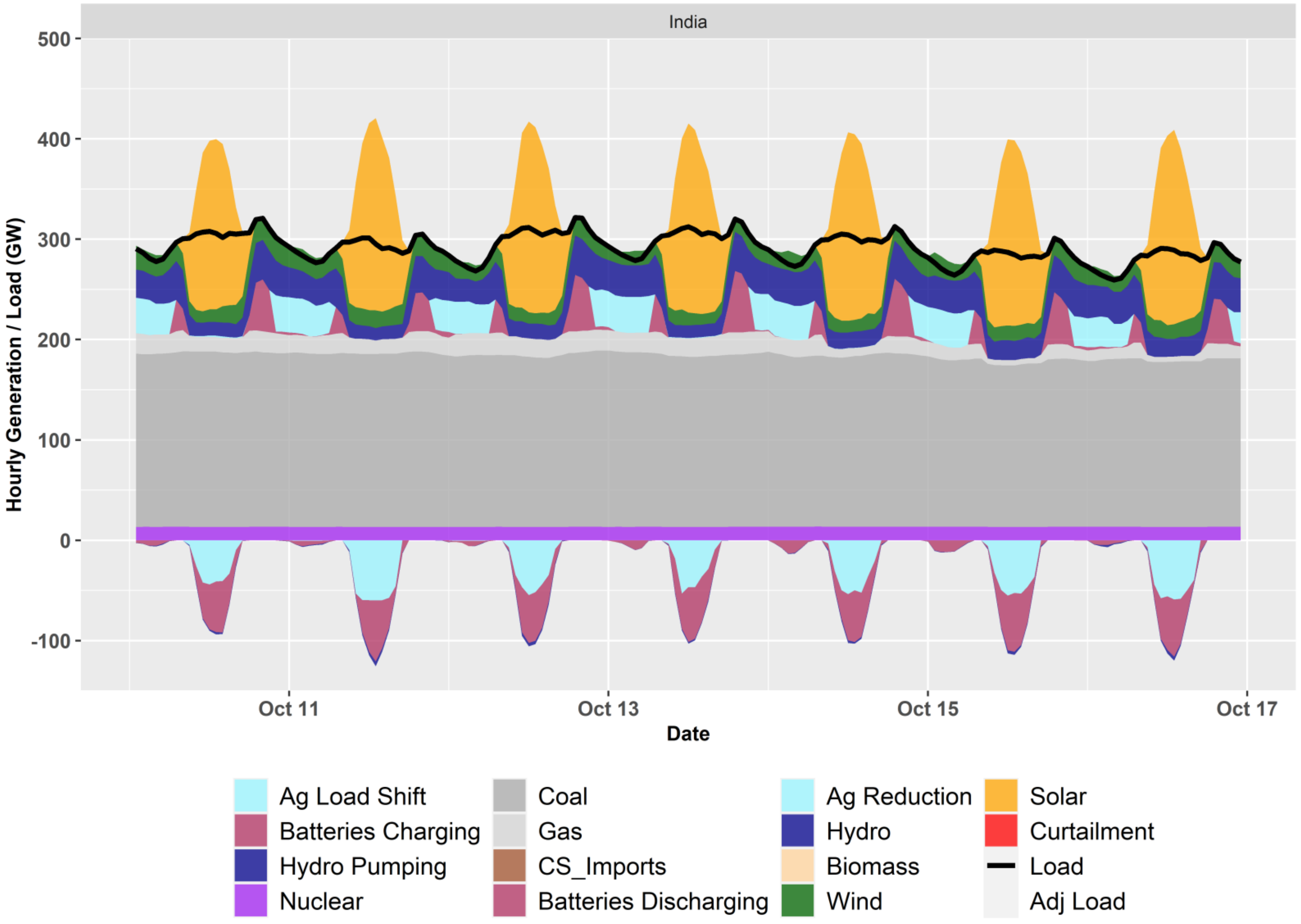


Chart shows results from simulating the hourly power plant level dispatch (8760 hours x ~2,500 generation units x 75 interstate transmission corridors) during the **highest net load week in FY 2030**.

Net Load Peak (National)
= 307 GW on Oct 13 at 7:00 PM

Coal and Nuclear generate at near full capacity
Coal = ~175 GW
Nuclear = ~13 GW

Supply side FRs play a crucial role in meeting the net load peak
Battery = ~60 GW
Gas = ~22 GW
Hydro = ~40 GW (incl small hydro)

Detailed results available at:
https://public.tableau.com/profile/nikit.abhyankar#!/vizhome/FRINationalDispatchVizv2/DispatchSummary

How would the system be dispatched in 2030? (e.g. Primary Least Cost Pathway)

Chart shows average hourly power system dispatch in FY 2030 for key months

Out of the 229 GW of total coal capacity, ~185 GW of coal operates with capacity factor >70%.
The remaining ~40 GW capacity runs at a capacity factor of ~30-40% (➔ Potentially stressed).

Battery storage charges during the day and discharges during evening and morning peak hours (4-6 hours/day).

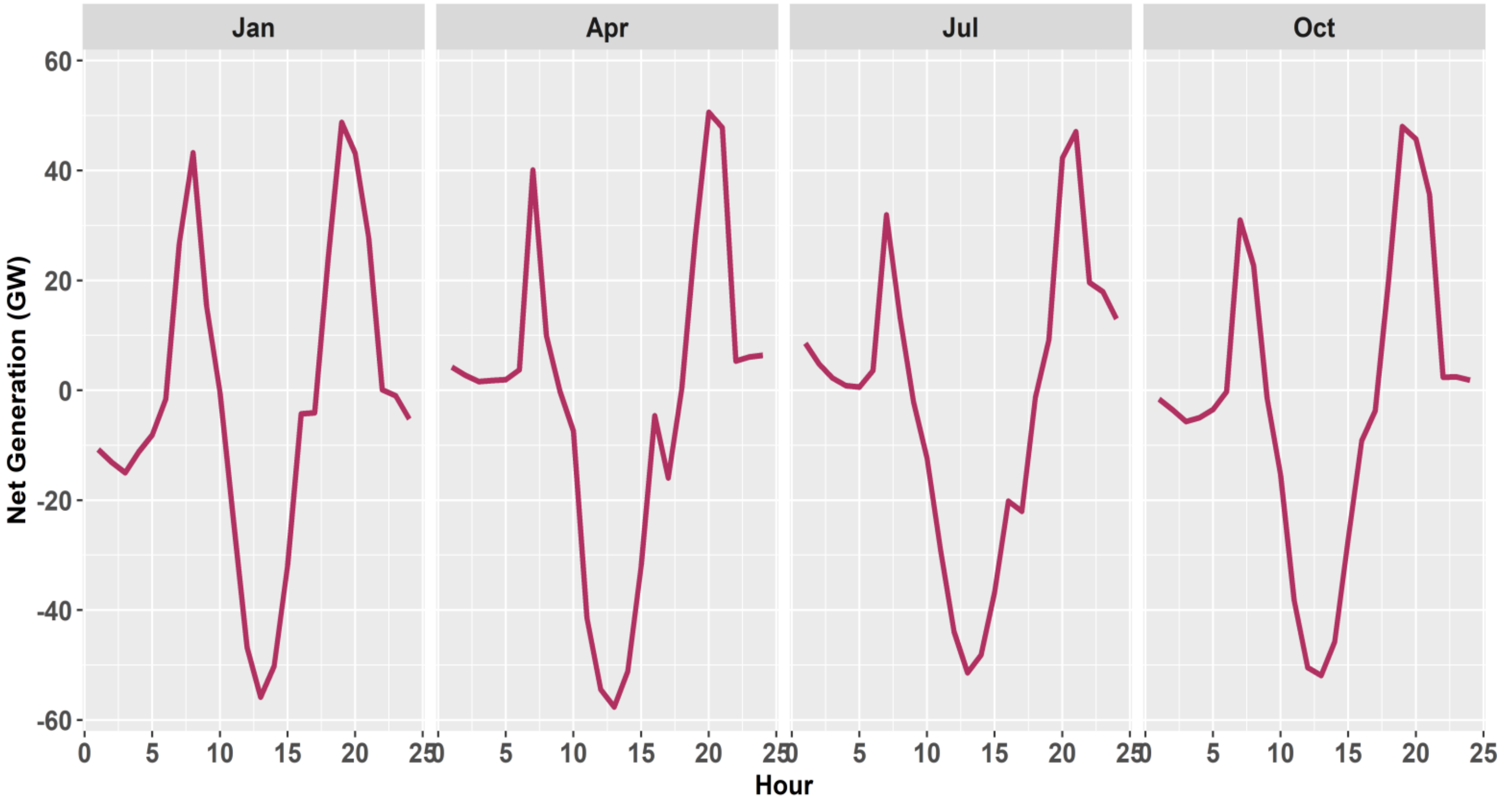
Agricultural load shift offers significant night time load reduction potential.

Gas mainly provides seasonal balancing support during low-RE season (Oct-Feb)

Detailed results available at:
https://public.tableau.com/profile/nikit.abhyankar#!/vizhome/FRINationalDispatchVizv2/DispatchSummary

How much storage is required and how is it operated ?

Average charge (negative) and discharge (positive) operation of energy storage in FY 2030 (Primary Least Cost case)



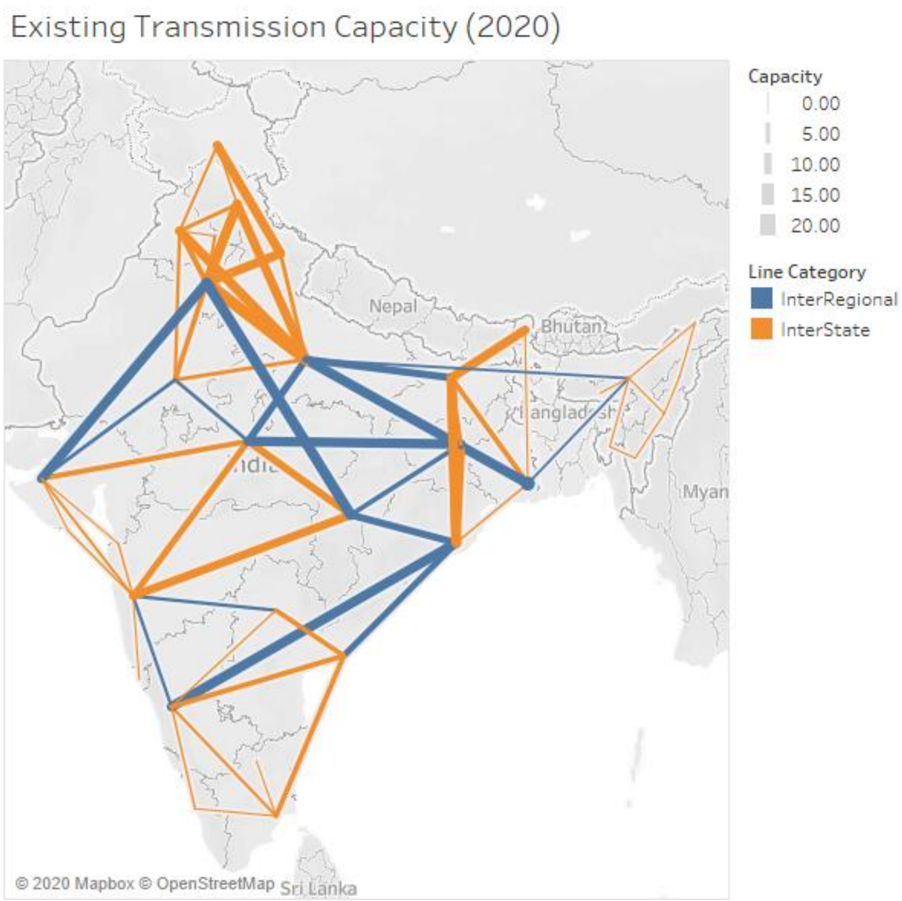
Optimal energy storage requirement (All-India)

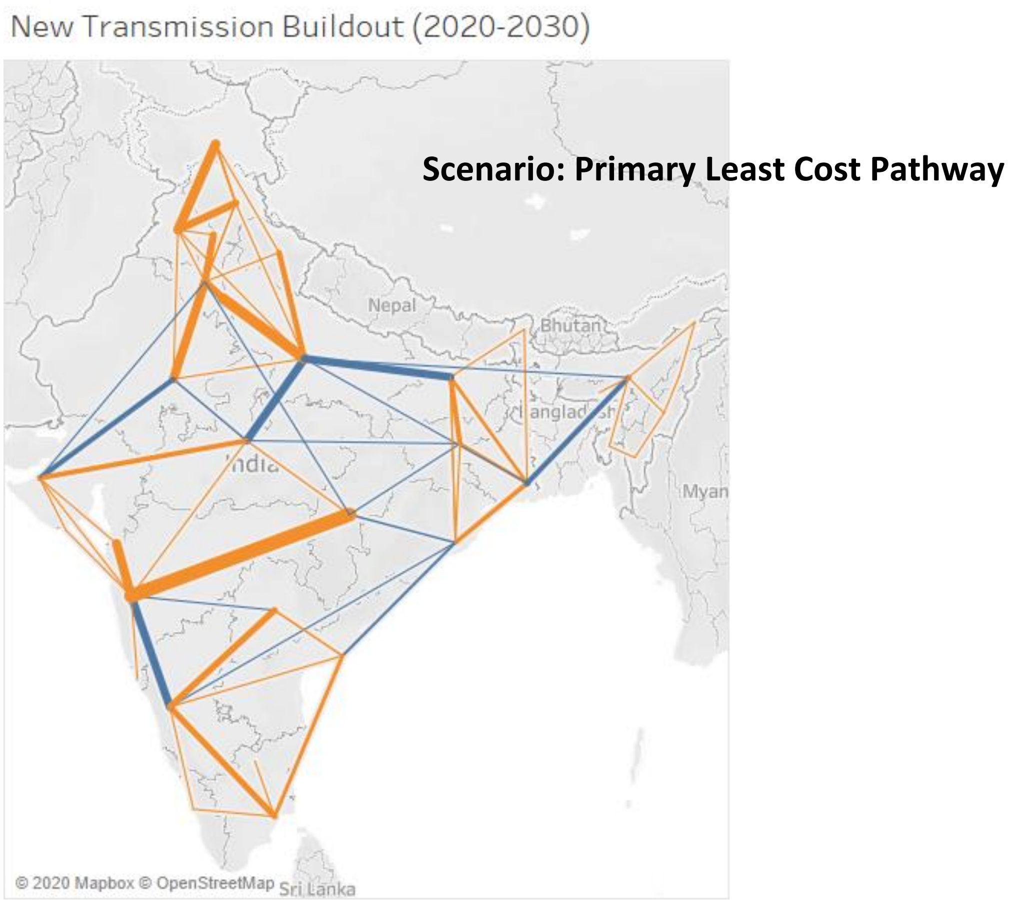
2025	2027	2030
12 GW/ 48 GWh	31 GW/ 125 GWh	63 GW/ 252 GWh

Batteries mainly charge during the day (except in winter when some early morning charging is required due to low solar generation), and discharge during evening and morning peak hours (4-6 hours/day).

Storage would be a critical source of flexibility starting as early as 2023, especially in states with high solar deployment and low hydro resources such as Rajasthan, Madhya Pradesh, Gujarat etc.

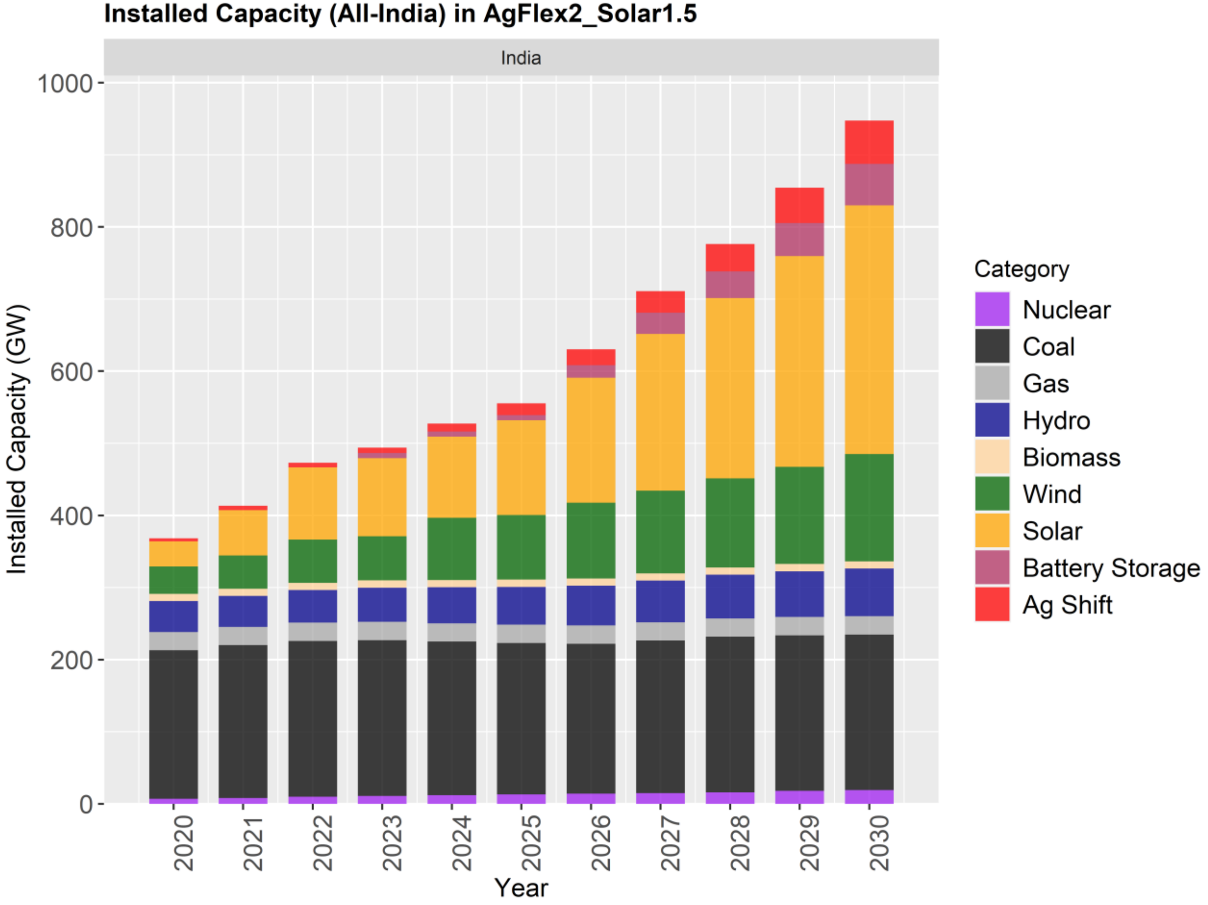
~140 GW of additional interstate transmission needs to be built





- Between 2020 and 2030, ~140 GW of additional transfer capacity needs to be built (~40 GW on inter-regional corridors and ~100 GW on interstate corridors) in the primary least cost scenario
- Average transmission buildout cost by FY 2030 = ~Rs 0.08 - 0.10 /kWh
- In general, as RE penetration increases, the need for additional transmission increases; if MBED is implemented, cost-effectiveness of for additional transmission investments increases significantly.

What is the impact of low renewable energy and battery prices ?

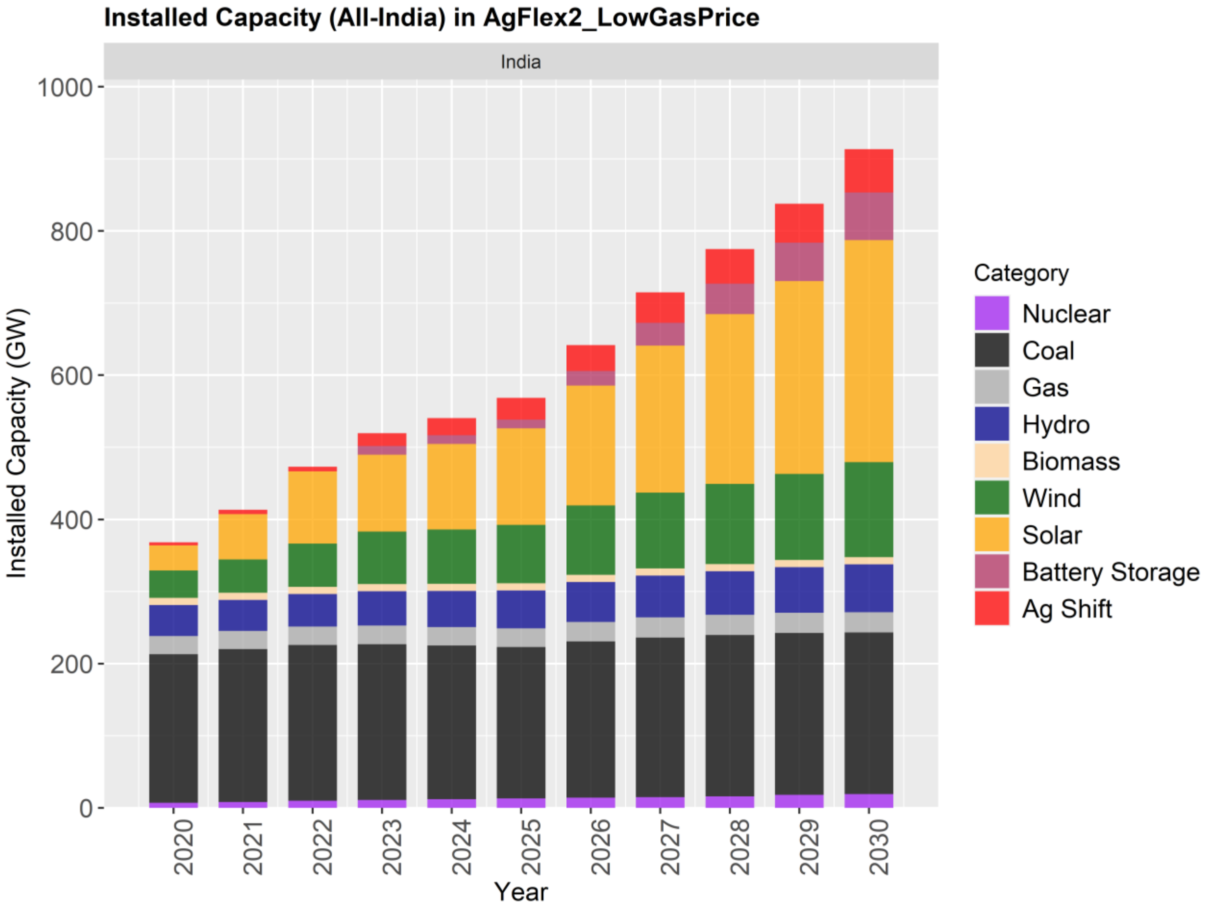


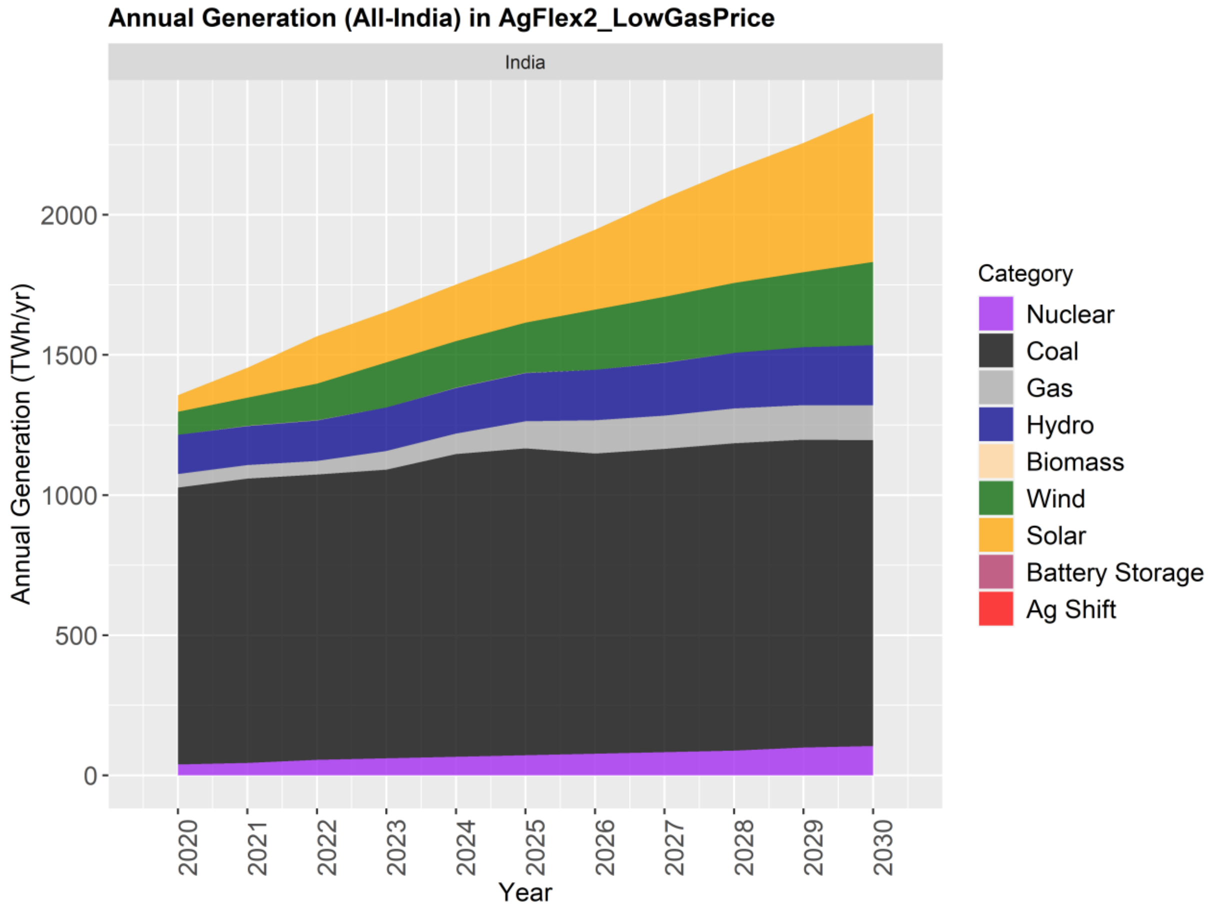
Installed Capacity (FY 2030)

Technology	Low RE and Storage Prices	Primary Least Cost (Base RE Cost)
Coal	***206***	229
Gas	25	25
Nuclear	19	19
Hydro	67	67
Wind	***147***	142
Solar	***385***	307
Other RE	15	15
Batteries	***84***	63

- If RE and storage prices per global trends (by 2030, solar LCOE = Rs 1.5/kWh and battery LCOS = Rs 3/kWh), RE penetration increases to >500 GW (>40% by energy).
- RE share in total electricity generation is >40% (~1,000 TWh/yr), while coal generation plateaus at ~1000 TWh/yr.
- Average Cost of Generation (2030) = Rs 3.50/kWh, as compared with Rs 3.59/kWh in the primary least cost pathway

What is the impact of low LNG price ?

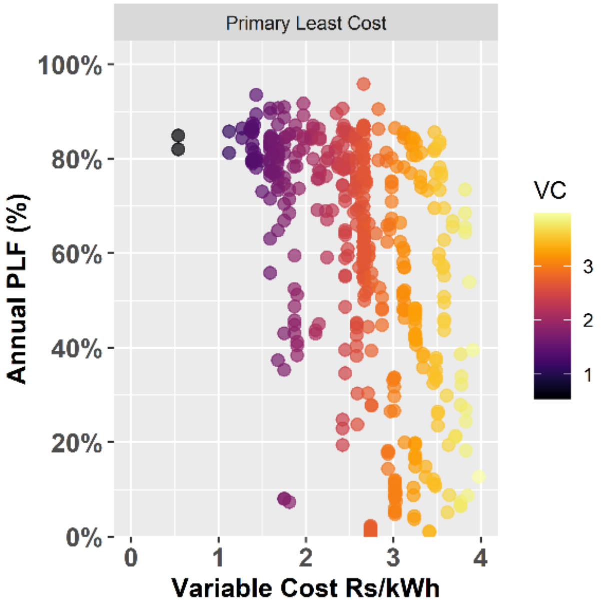


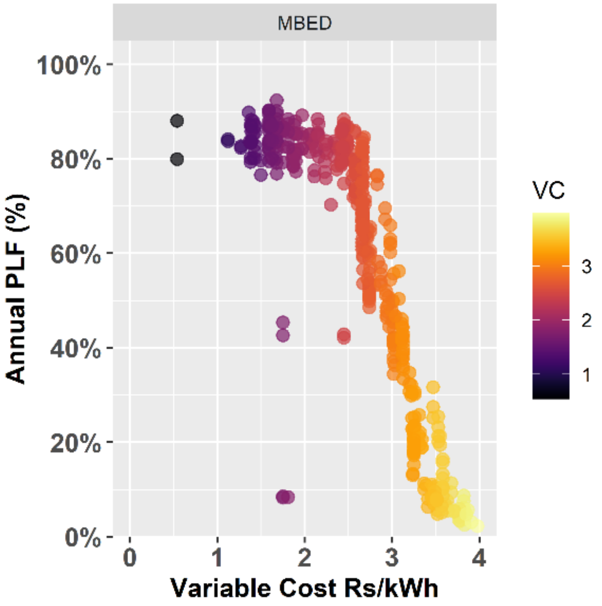


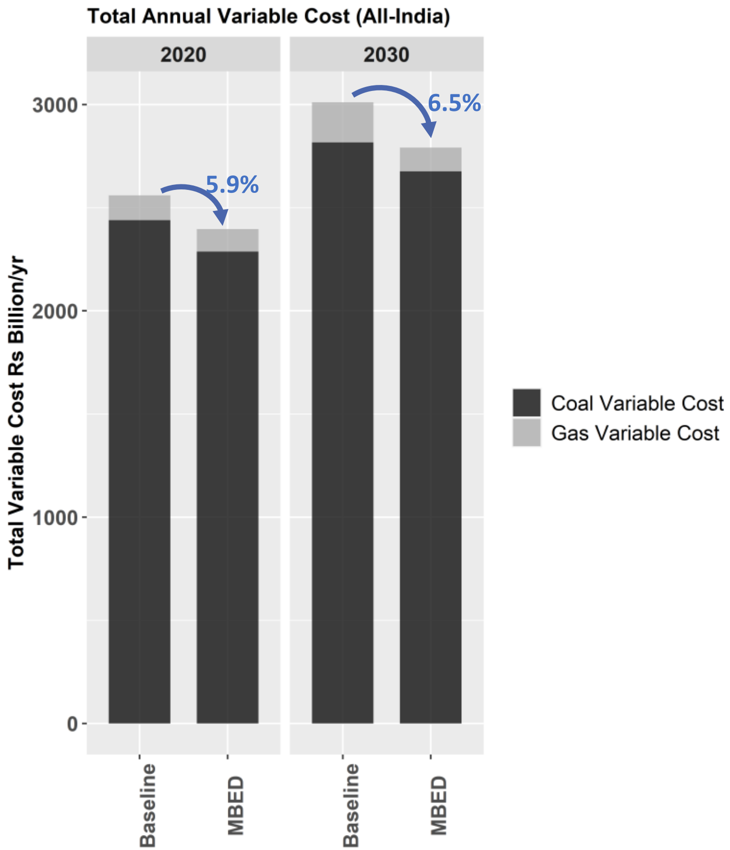
- If LNG price drops to $4.5/MMBTU, LNG starts competing with expensive coal power plants. Although new gas-fired assets are still not cost-effective at this LNG price, gas generation increases to ~120 TWh/yr by 2030 (compared with ~50 TWh/yr in the primary least cost case).
- Domestic gas availability for power sector = ~8.5 bcm/yr (~23 mmscmd); LNG consumption by 2030 = ~14 bcm/yr (~10 MTPA)
- There is no major change in the solar, wind, or coal capacity relative to the primary least cost case.
- Average Cost of Generation (2030) = Rs 3.58/kWh, as compared with Rs 3.59/kWh in the primary least cost pathway

What is the impact of Market Based Economic Dispatch (MBED)?

Each point plots PLF of an individual coal / gas unit in the Primary Least Cost case in FY 2030 against its variable cost (VC).
Color density also indicates the unit's VC in Rs/kWh.







In the current dispatch system, each state would dispatch its own / contracted capacity first, leading to a sub-optimal dispatch nationally. Several low VC thermal plants may run at low PLFs.

With MBED, power plant dispatch will be optimized nationally. As a result, low VC units will be dispatched more (subject to physical transmission constraints), resulting in a reduction in the overall system costs.

With MBED, due to the efficient power plant dispatch, total variable (fuel) costs will reduce by 6.5% by 2030.

Key Conclusions

- India's current pathway of significant RE as well as coal buildout may present existing coal fleet and new RE assets with financial and technical risks (operational challenges, RE curtailment, and low coal PLF)

- The Least Cost Capacity Expansion is pointing to the following results:
  - A combination of RE (450-500GW) + FRs: 30-60GW energy storage, 60GW of load shifting, flexible operation of the 25 GW of gas, ~140GW of interstate/inter-regional transmission, and market-based economic dispatch (MBED)
  - 23 GW of net addition to the coal capacity by 2030 is cost-effective (may be higher in case of deployment barriers or RE/storage costs do not decline)
  - The complementarity of FRs working in tandem maintains grid dependability in view of high RE penetration

- Study outcomes point to some key policy and regulatory strategies
  - Owing to the shorter lead times, FRs can make system planning flexible and robust in responding to deviations from the expected trajectory (e.g. lower or higher load growth)
  - Energy storage will play a key role and will need an appropriate regulatory framework for deployment to capture its full value
  - Gas is a source of flexibility for a high-RE grid; supply/pipeline flexibility and regulatory issues need to be addressed
  - Nuanced resource adequacy framework needed to drive planning and procurement strategies, and avoiding potential future stranded assets

Policy/Regulatory Recommendations

- **Resource Adequacy (RA) Framework**
  - National study to determine optimal resource mix for given demand; reserve margin study to determine RA requirement
  - Institute RA program at the national level, with monthly or seasonal RA requirements allocated to the states; facilitate capacity sharing among states
  - In the longer term, move towards national capacity markets with national pool for energy settlement (e.g., Market-Based Economic Dispatch, MBED)
- **Planning and procurement**
  - Integrate RA requirements into discom/state planning and procurement
  - "All-source" procurement for new resources at state/discom level to account for the interactions among different resources and arrive at least-cost mix
- **Markets and system operations**
  - Adjust electricity market rules to enable storage to provide and be compensated for its full functionality
  - Better align market and system operations to enable efficient ancillary services markets and manage potential transmission congestion; accelerate implementation of MBED
- **Gas sector reforms**
  - Focus on operational and contractual flexibility for gas pipelines to facilitate flexible operation of existing gas-fired power plants

Click here for the report on the modeling study.

Click here for the report on regulatory recommendations.

Contact:

Dr. Nikit Abhyankar NAbhyankar@lbl.gov

Shruti Deorah SMDeorah@lbl.gov

Additional Material

Summary of the Key Results

Scenarios			Results (FY 2030)					
#	Scenario	Details	Coal (GW)	Gas (GW)	Solar (GW_{DC})	Wind (GW)	Storage (GW)	Avg Cost (Rs/kWh)
1	**Primary Least Cost**	Ag load shifts; 25GW Coal retires; EPS Load	229	25	307	142	63	3.59
2	**Low RE Cost**	RE + storage costs drop rapidly per recent trends	206	25	385	147	84	3.50
3	**High RE Cost** (w/ Supply Chain Challenges)	Significantly higher cost and deployment constraints for solar and batteries	242	45	220	142	32	3.63
4	**Low LNG Price**	LNG price = $4.5/MMBTU (landed)	224	28	308	132	66	3.58
5	**No Coal Retirement**	25GW coal (NEP) does not retire per plan	238	25	301	137	57	3.62
6	**Low Demand Growth**	Load growth is 25% lower (2030 Peak = 290GW)	206	25	230	109	32	3.64
7	**MBED**	National level economic dispatch	232	25	302	151	59	3.56
8	**CEA**	CEA Optimal Expansion Portfolio	266	25	280	140	27+10	#N/A

Detailed results for all cases could be found at: https://public.tableau.com/profile/nikit.abhyankar#!/vizhome/FRICapExPrelimResultsv2/Story1

- In general, the model is showing that building new RE+FRs is more cost-effective than building new coal power plants
- As expected, factors that decrease average generation costs are Ag Load Shifting, Low Gas Prices, and MBED, while low demand and supply chain constraints will drive average generation costs up

How does the study capture RE integration costs?

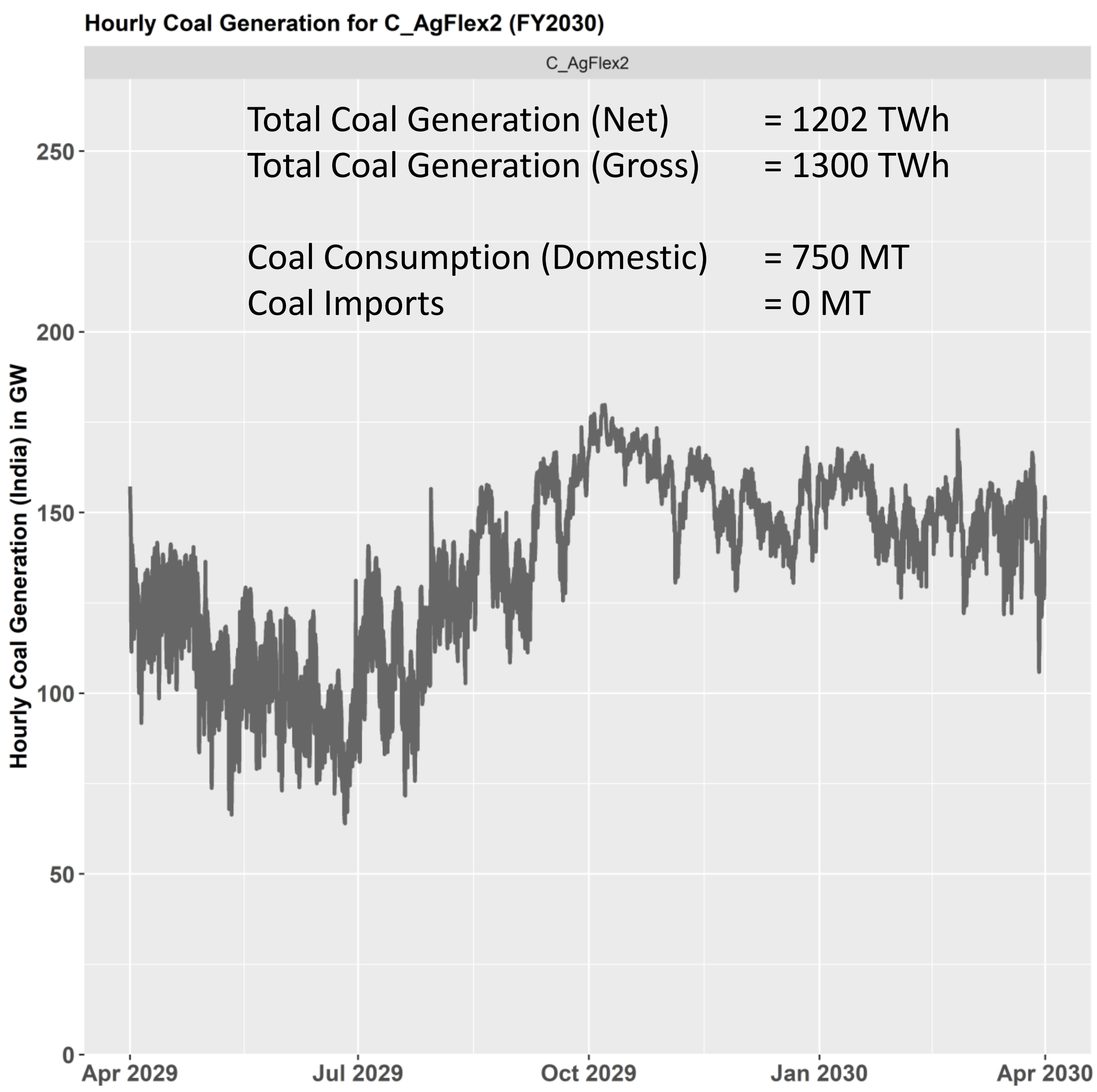
- Costs due to diurnal / seasonal nature of RE generation
  - E.g. need for energy storage, part-load operation of thermal plants during RE hours, seasonal operation / low-PLF of certain capacity, RE curtailment etc.
  - ➔ Model captures these costs

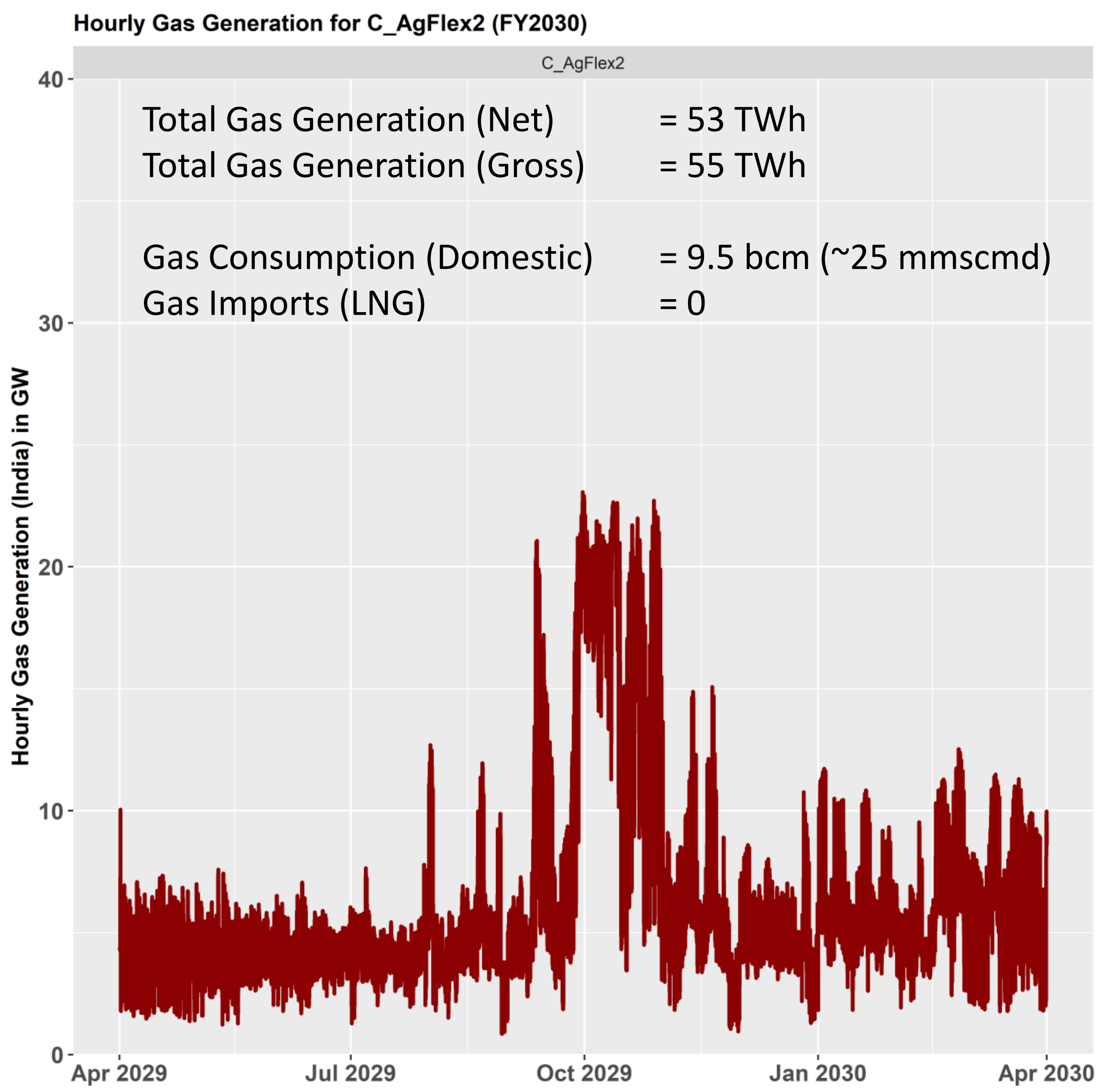
- Costs due to inherent intermittency in RE generation
  - May increase ramping / ancillary service requirement and RE curtailment
  - Model simulates hourly dispatch; thermal power plants need to abide by the ramping constraints
  - ➔ Model captures costs of meeting hourly RE intermittency
  - Does not include costs due to sub-hourly variability or forecast errors, which are typically small

- Costs due to additional infrastructure investments
  - E.g. additional transmission costs owing to geographic concentration of some RE resources (e.g., wind) and additional ramping requirement
  - ➔ Model captures, at a high level, transmission investments and costs (e.g., inter-regional and inter-state)

- Other costs
  - Wear and tear of thermal power plants due to cycling, ramping etc (➔ Model shows how FRs can help minimize cycling)
  - Reduction in the system inertia, etc. (small cost but needs more nuanced assessment)

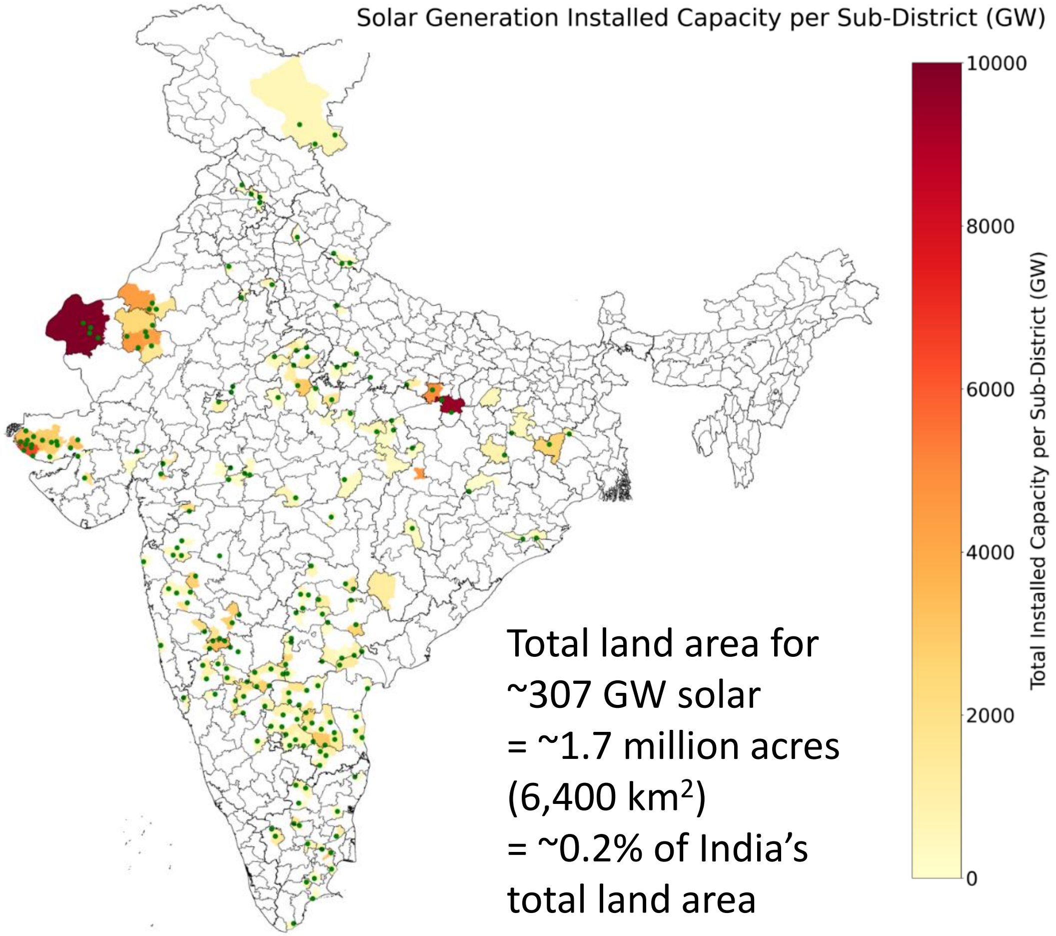
Coal and Gas Generation (ex-bus) in the Primary Least Cost Case FY 2030





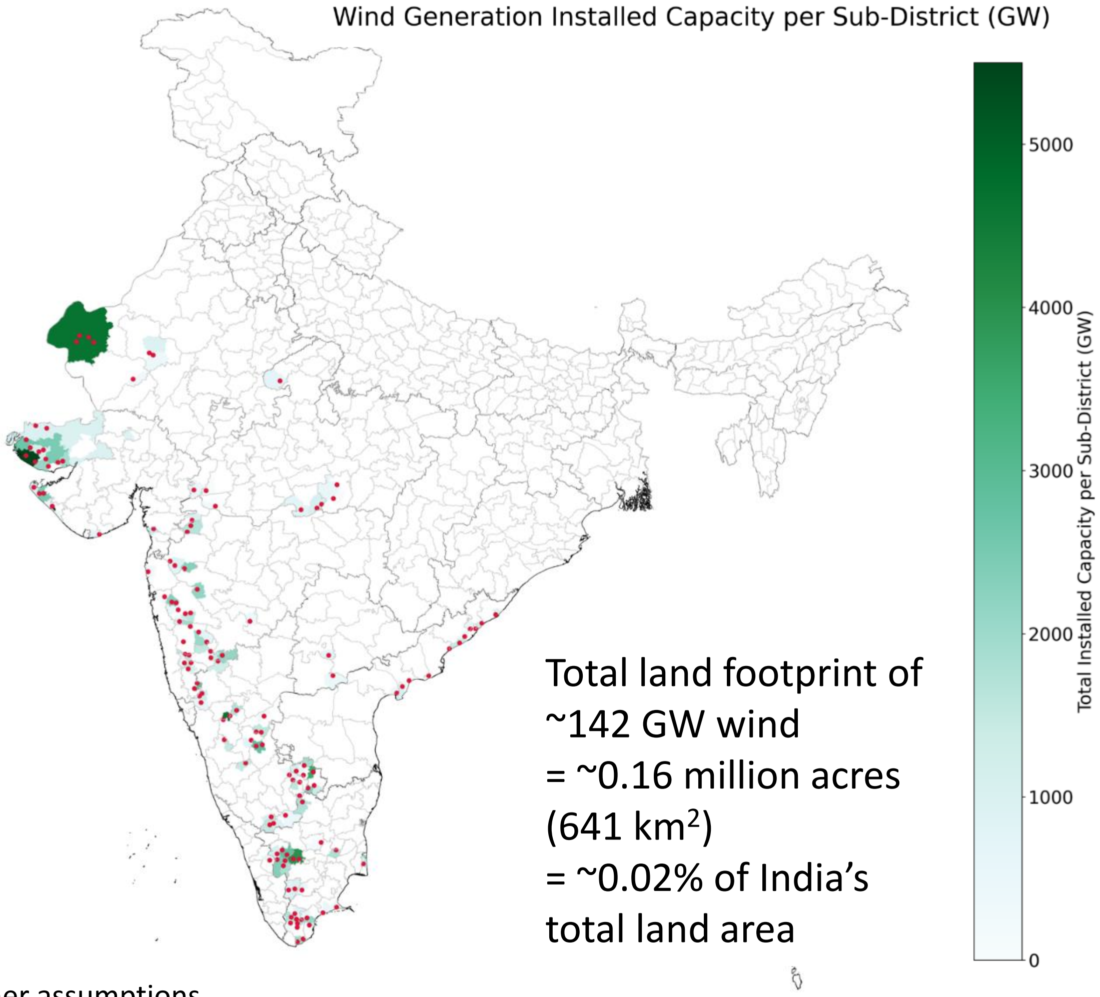
Where could the 450 GW RE capacity be sited ?

Solar



Total land area for ~307 GW solar
= ~1.7 million acres (6,400 km^2)
= ~0.2% of India's total land area

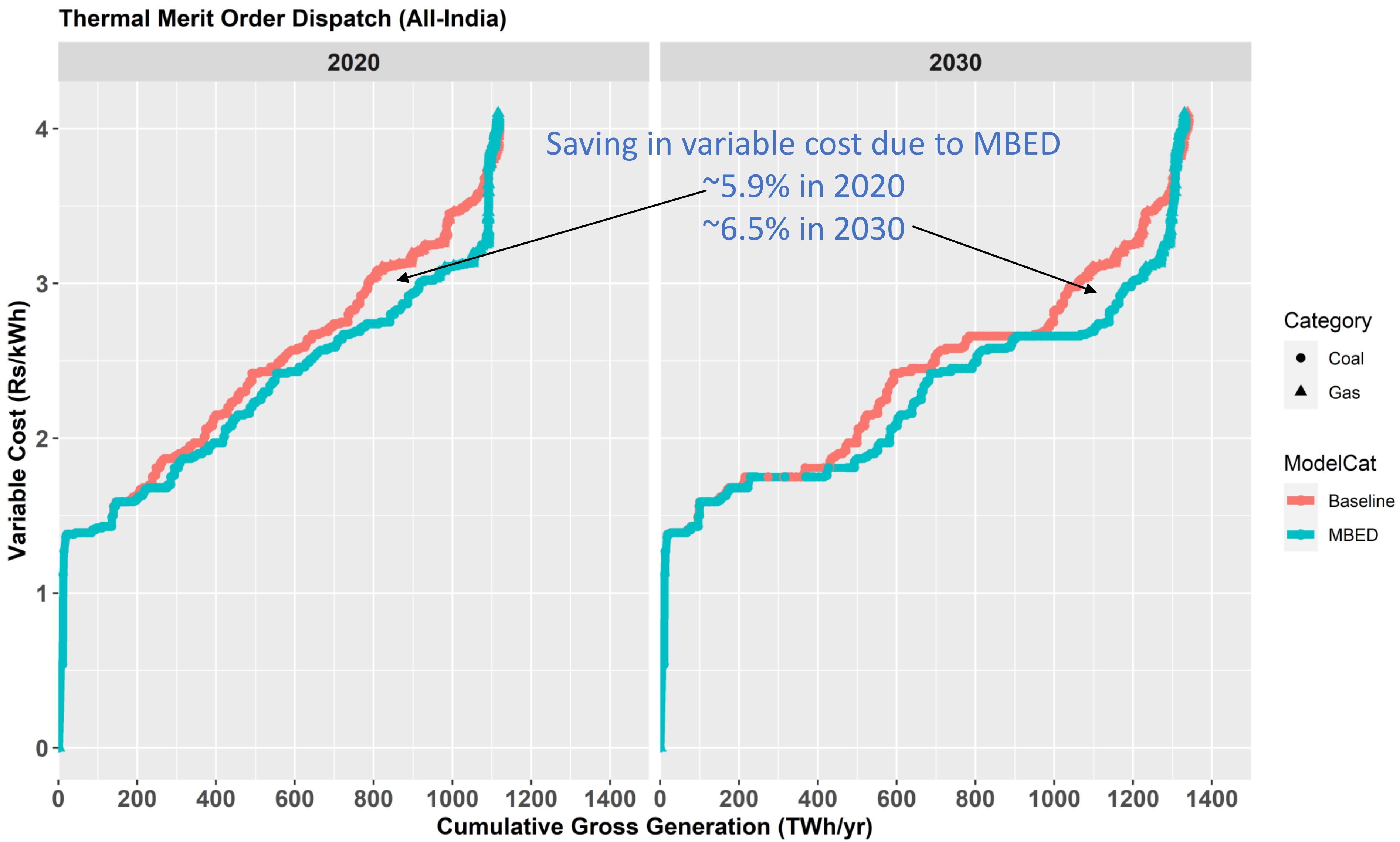
Wind



Total land footprint of ~142 GW wind
= ~0.16 million acres (641 km^2)
= ~0.02% of India's total land area

All underlying data and other assumptions are available at http://mapre.lbl.gov

MBED results in efficient dispatch saving total variable cost by ~6-7%



Click here for the report on the modeling study.

Click here for the report on regulatory recommendations.

Contact:

Dr. Nikit Abhyankar NAbhyankar@lbl.gov
Shruti Deorah SMDeorah@lbl.gov