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Technical Report

Rapid Deployment of Solar and Storage Is the Main Option for Avoiding Power Shortages in India

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July 2024

Executive Summary

1. **Power shortages likely**: Due to rapid electricity demand growth, India will likely experience significant evening power shortages by 2027 (20-40 GW), even if all the thermal & hydro capacity currently under construction comes online as planned.

2. **Storage deployment combined with solar can avoid shortages:** Large-scale solar + storage deployment is the main option left to avoid power shortages, as they can be deployed much faster than new thermal and hydro assets. By 2027, 100-120 GW of new solar, out of which 50-100 GW co-located with 16-30 GW x 4-6 hours of storage, can avoid shortages.

3. **Solar + Storage is highly economical:** Recent gigawatt-scale solar + storage auction results, with a record low price of Rs 3.4/kWh, also show that such deployment will be highly economical.

4. **Policy support needed to ensure fast deployment at scale:** Fiscal incentives combined with mandates are likely required to ensure rapid storage deployment at scale to ensure security and reliability.

5. **Significant RE and storage expansion in the long-run**: India's electricity demand will quadruple by 2047, necessitating a massive expansion of low-cost RE and storage to reduce consumer bills and sustainably power the rapid economic growth.

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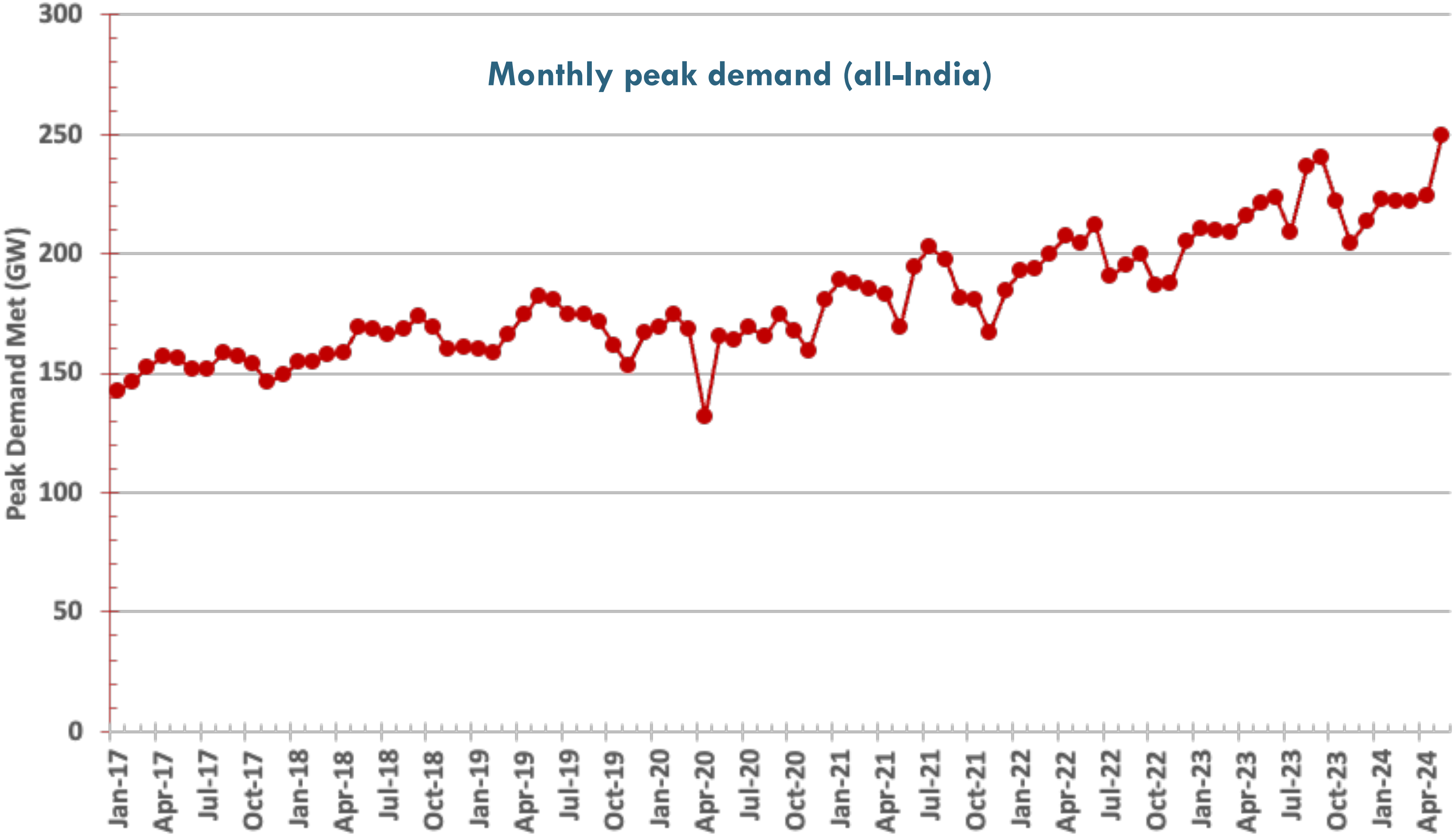
1. Power shortages likely

India's electricity demand is doubling every decade; peak load reached 250 GW in May 2024 causing significant system stress



Data Source: CEA Monthly Executive Summaries (2017-2024)

India's electricity demand grew by 7% in 2023, compared to a global average of 2.2%.

Between May 2019 and May 2024, India's peak electricity demand increased by a staggering 68 GW, from 182 GW to 250 GW, representing an annual growth rate of 6.5%.

The post-COVID period has seen an even more dramatic increase, with peak demand shooting up by 46 GW in just two years, from 204 GW in May 2022 to 250 GW in May 2024.

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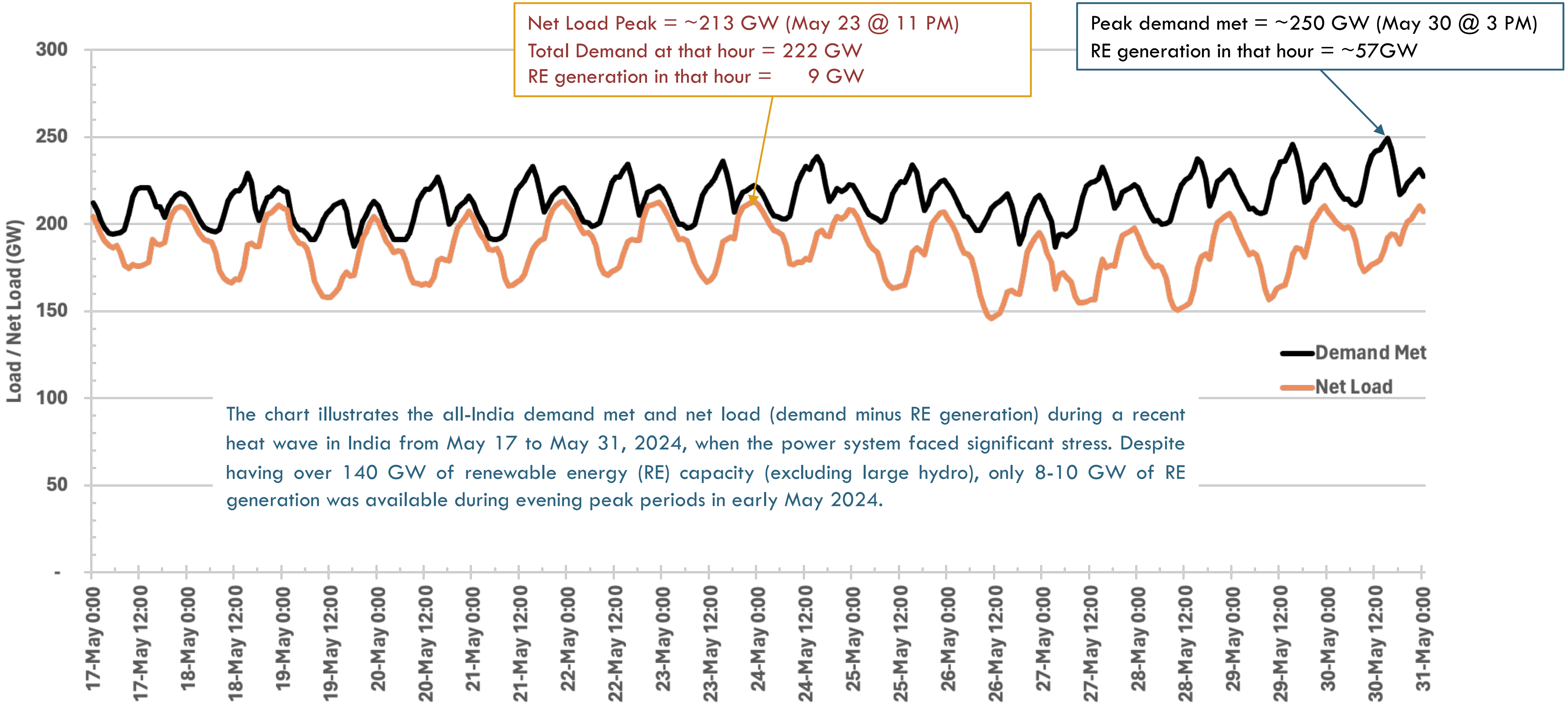
RE generation during evening / night peak hours is uncertain, highlighting the firm capacity need for grid reliability



The chart illustrates the all-India demand met and net load (demand minus RE generation) during a recent heat wave in India from May 17 to May 31, 2024, when the power system faced significant stress. Despite having over 140 GW of renewable energy (RE) capacity (excluding large hydro), only 8-10 GW of RE generation was available during evening peak periods in early May 2024.

Data Source: CSEP Carbon Tracker (www.carbontracker.in)

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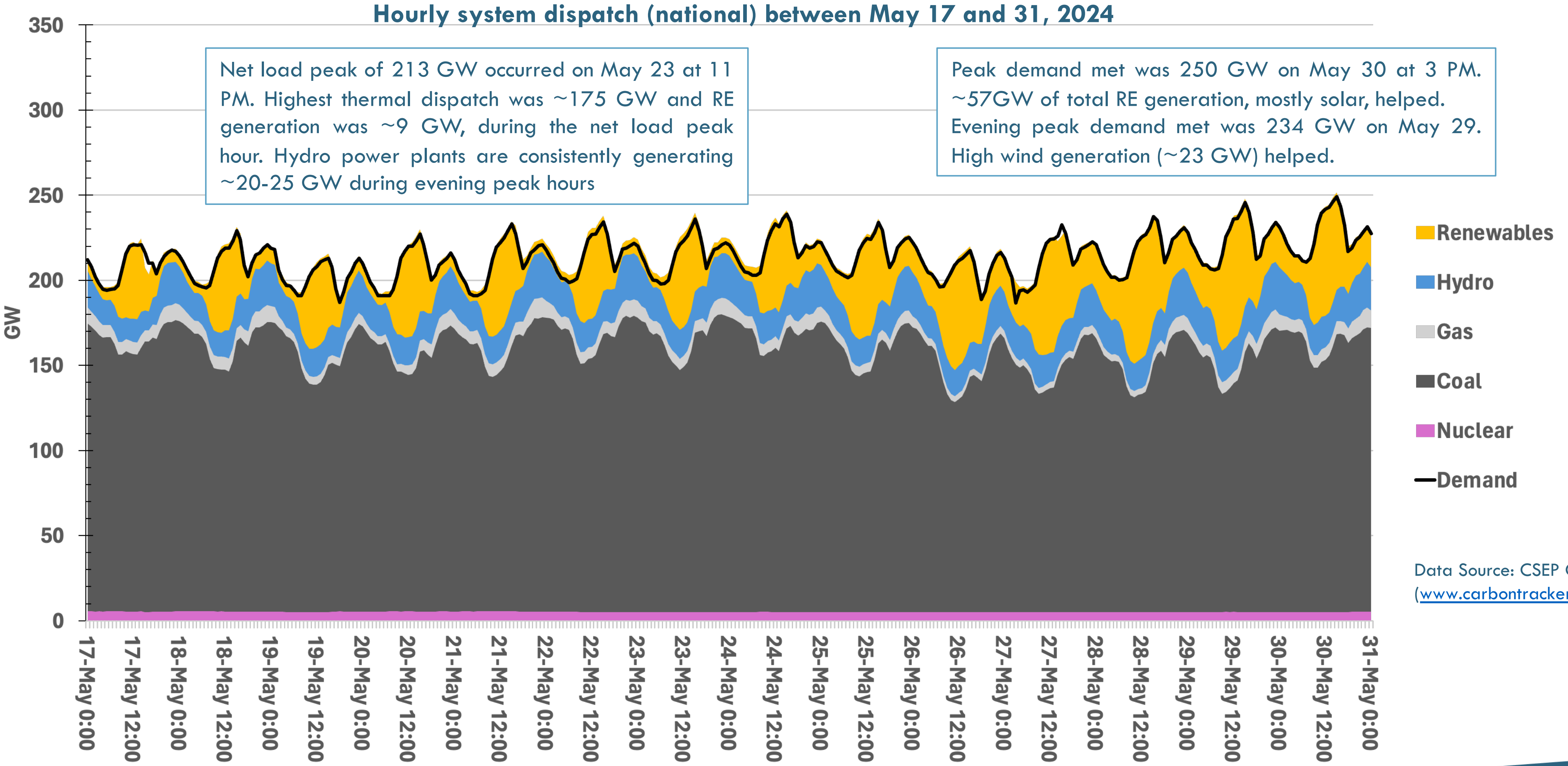
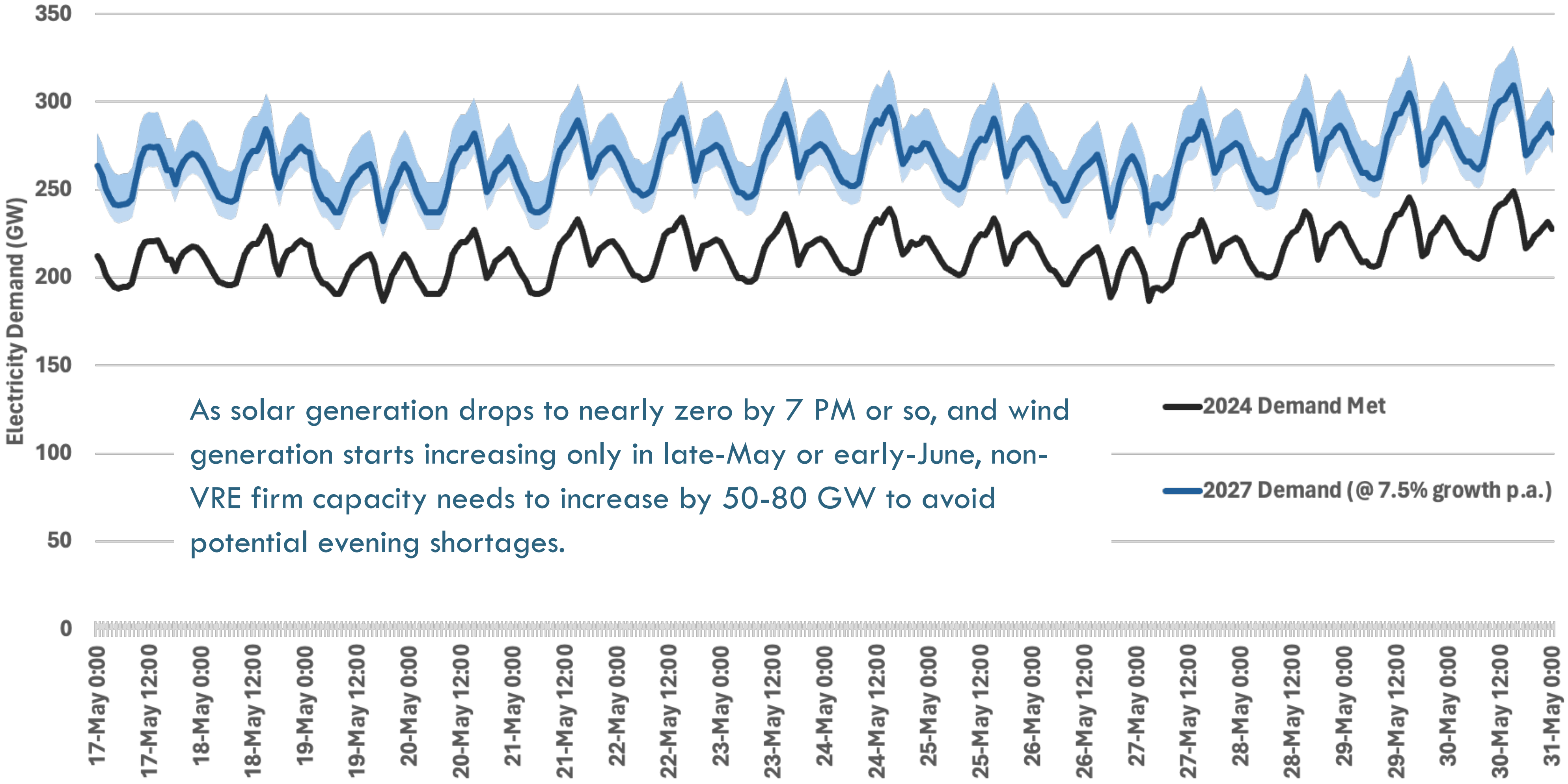
How was the system dispatched during summer peak of 2024 ?



Data Source: CSEP Carbon Tracker (www.carbontracker.in)

By 2027, summer evening peak could increase by 50-80 GW and will likely go beyond 300 GW



As solar generation drops to nearly zero by 7 PM or so, and wind generation starts increasing only in late-May or early-June, non-VRE firm capacity needs to increase by 50-80 GW to avoid potential evening shortages.

Solid blue line shows 2027 projected load at 7.5% p.a. load growth.

Error bands show 6% and 10% load growth cases.

Solid black line shows 2024 actual demand met.

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~41 GW of non-VRE firm capacity is under construction scheduled to be commissioned by FY 2028

	Coal	Hydro	Nuclear	Total
FY 2025	14,040	5,228	0	**19,268**
FY 2026	2,400	4,550	1,400	**8,350**
FY 2027	2,780	2,530	1,400	**6,710**
FY 2028	2,260	510	4,000	**6,770**
Total	**21,480**	**12,818**	**6,800**	**41,098**

Data Source: CEA Thermal and Hydro Performance Review for Coal and Hydro capacities, respectively.
CEA's National Power Plan for Nuclear.

By 2027, if electricity demand grows beyond 6% p.a., significant evening shortages are likely

	Formula	Demand growth = 6% p.a.	Demand growth = 7.5% p.a.	Demand growth = 10% p.a.
Evening Peak in 2024	A	234	234	234
Evening Peak in 2027	B	279	291	311
Net Addition to the Evening Peak	**C = B-A**	**45**	**57**	**77**
New Firm Capacity (Under Construction)	D	41	41	41
Net Firm Capacity Shortfall in 2027	***E = C-D***	***4***	***16***	***36***

Note: All numbers in GW. This is a simplistic exercise for developing an intuitive understanding. These are NOT simulation results. An implicit assumption behind this simplistic calculation is that the maximum firm capacity support by the existing generation capacity cannot go beyond 2024 summer levels (~221 GW). Also, RE generation is not given any evening peak capacity credit. Finally, all new hydro capacity, including ROR plants have been generously given full capacity credit. No delays are assumed in commissioning the under-construction power plants.

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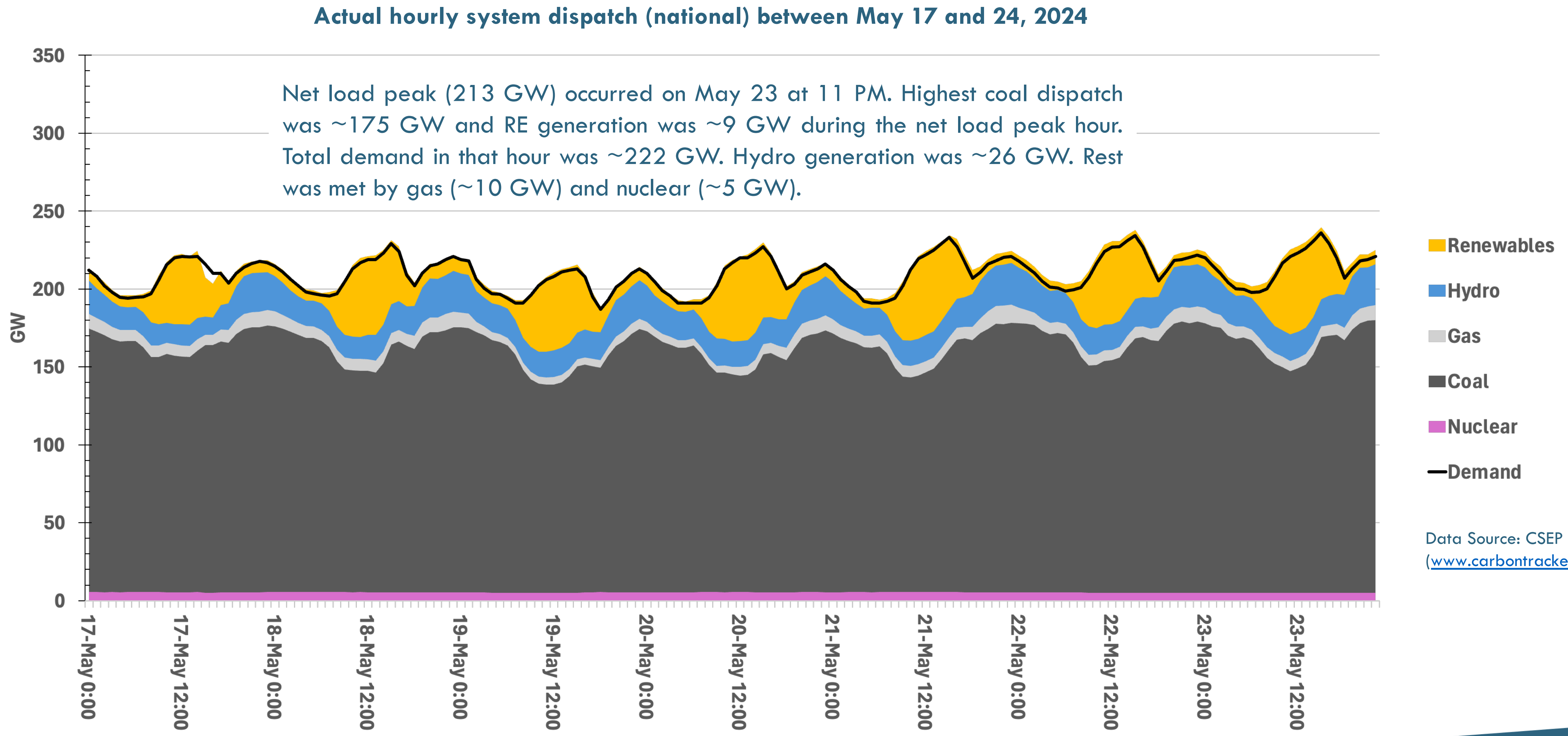
2. Storage deployment combined with solar can avoid shortages

Simulated grid dispatch results for a range of demand and supply scenarios in 2027 for the week of May 17, 2027

Actual system dispatch in 2024 during net load peak week



Data Source: CSEP Carbon Tracker (www.carbontracker.in)

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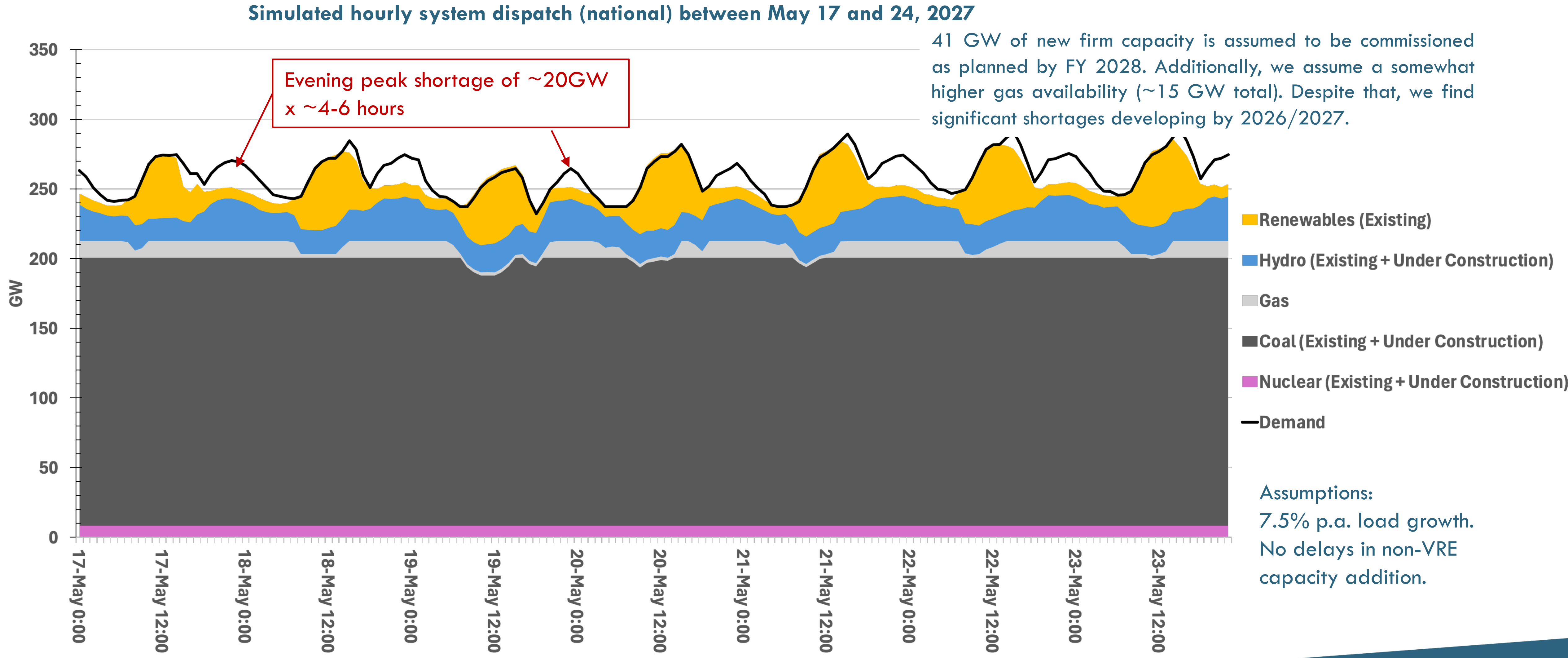
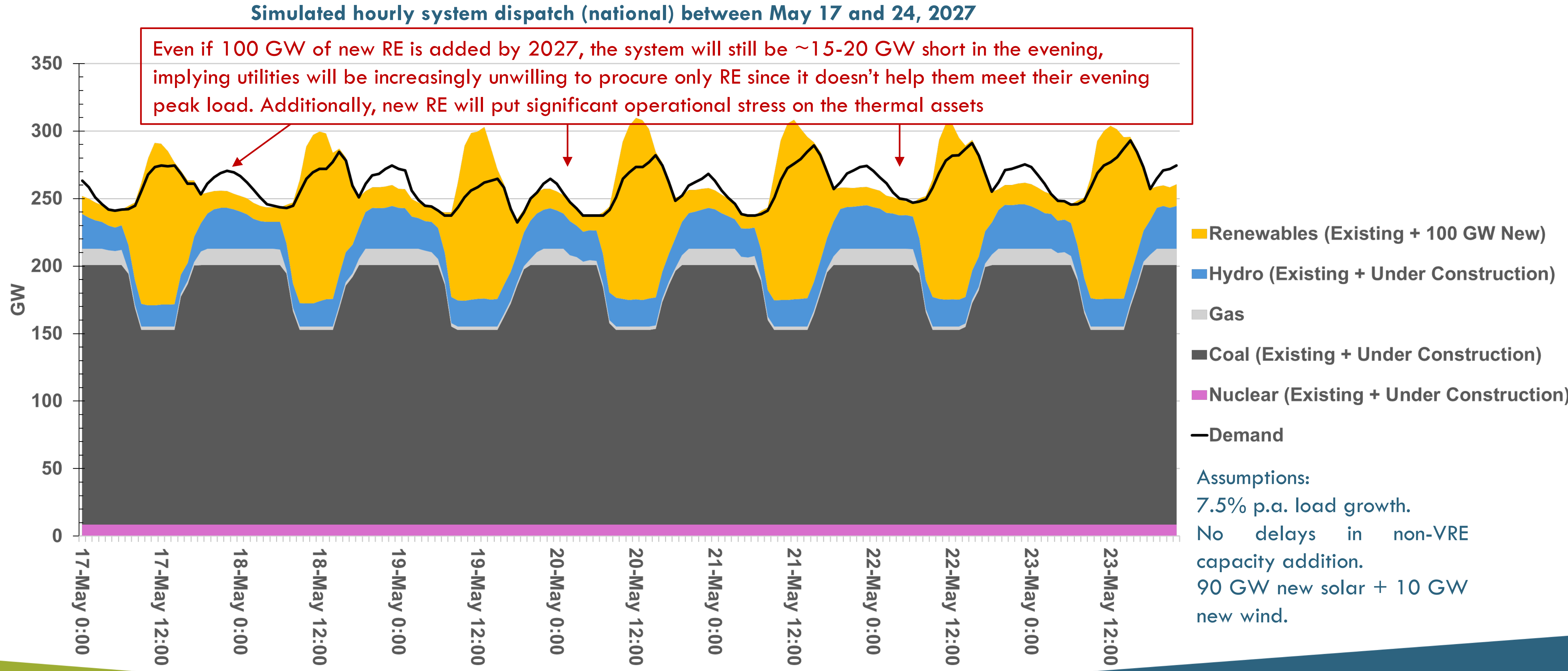
By 2027, even if 41GW of new firm capacity is added, system will be short by ~20 GW in the evening / night

41 GW of new firm capacity is assumed to be commissioned as planned by FY 2028. Additionally, we assume a somewhat higher gas availability (~15 GW total). Despite that, we find significant shortages developing by 2026/2027.



Assumptions:
7.5% p.a. load growth.
No delays in non-VRE capacity addition.

Even if 100 GW of new RE is added, evening peak shortages will still occur by 2027



Assumptions:
7.5% p.a. load growth.
No delays in non-VRE capacity addition.
90 GW new solar + 10 GW new wind.

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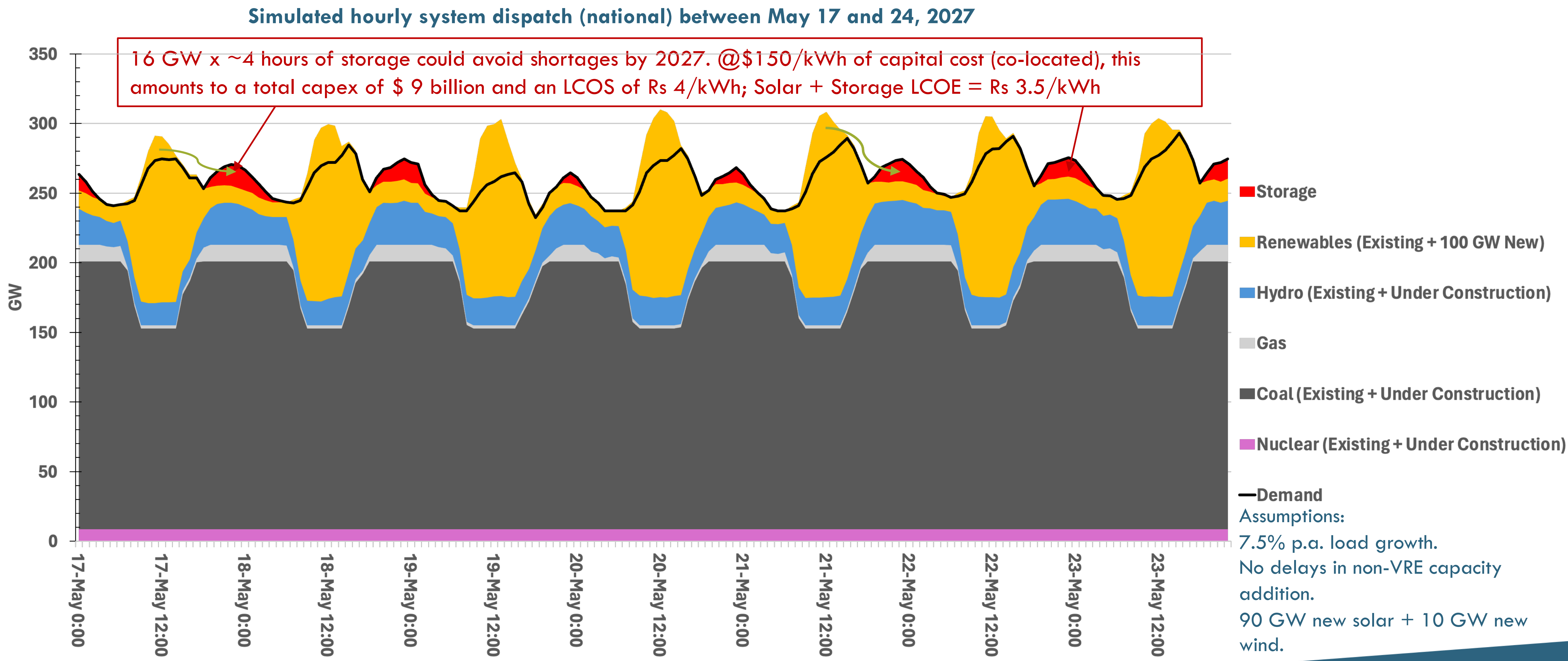
50 GW new solar, co-located with 16 GW/62 GWh of storage (~20% of daily solar gen), shortages could be avoided



Assumptions:

7.5% p.a. load growth.

No delays in non-VRE capacity addition.

90 GW new solar + 10 GW new wind.

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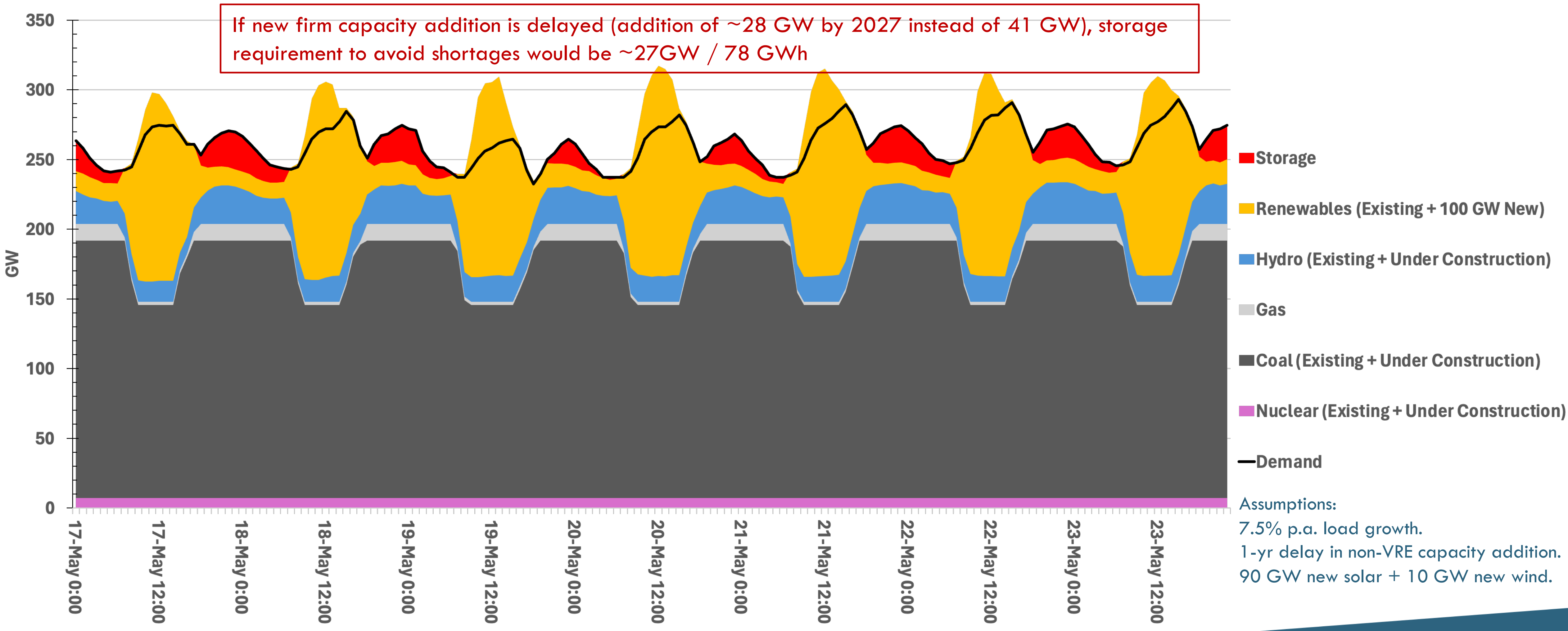
If new firm capacity commissioning gets delayed, shortages could start in 2025, reaching ~25-30 GW by 2027

Simulated hourly system dispatch (national) between May 17 and 24, 2027



Assumptions:
7.5% p.a. load growth.
1-yr delay in non-VRE capacity addition.
90 GW new solar + 10 GW new wind.

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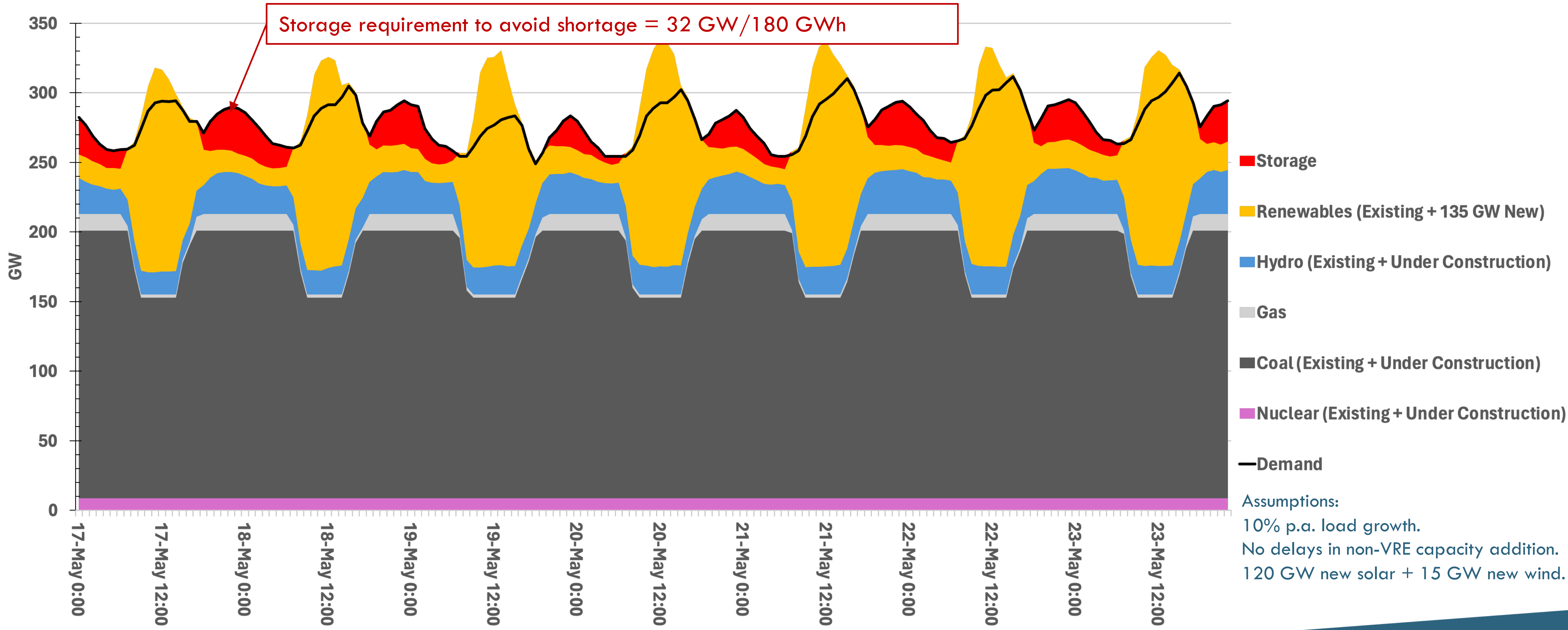
If demand grows by 10% p.a., evening peak shortage could increase to ~32GW, despite 41 GW firm + 135 GW RE addition

Simulated hourly system dispatch (national) between May 17 and 24, 2027



Assumptions:
10% p.a. load growth.
No delays in non-VRE capacity addition.
120 GW new solar + 15 GW new wind.

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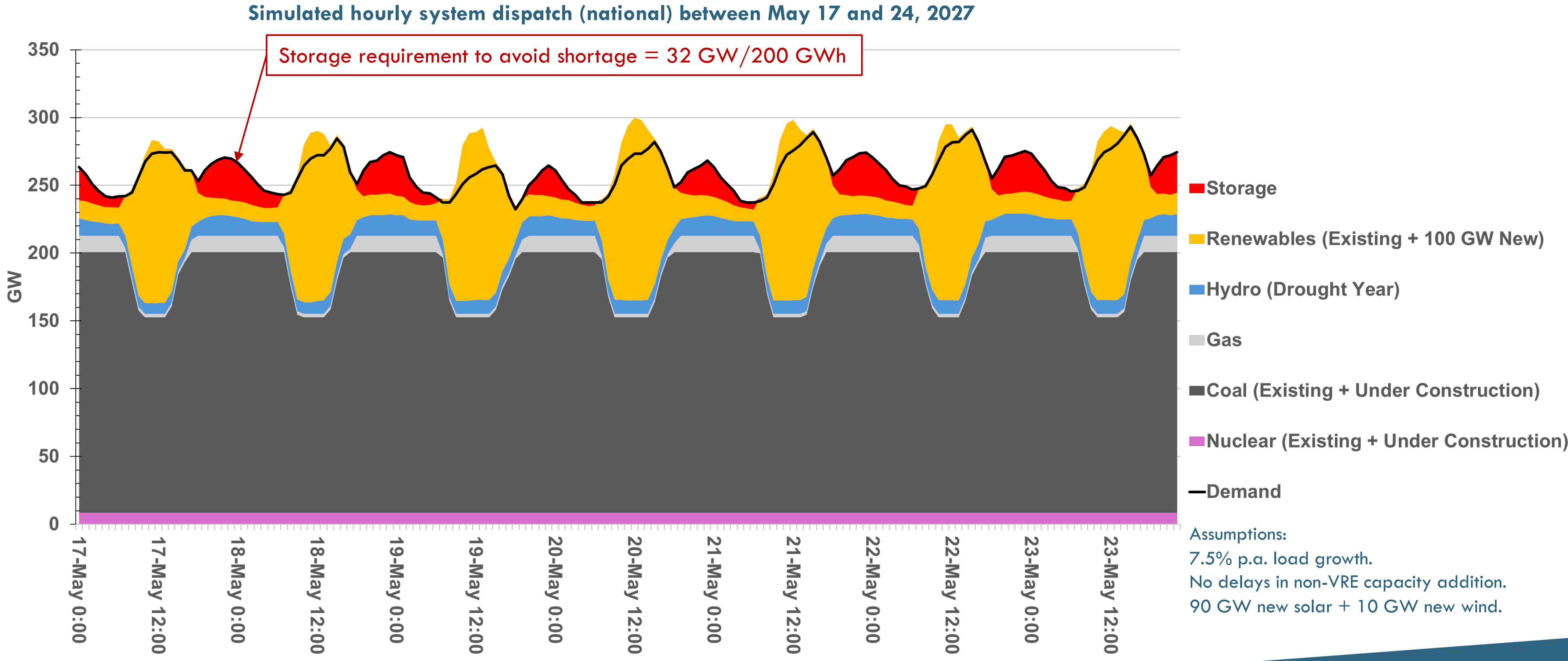
In case of a drought (~50% reduction in hydro generation), evening peak shortage could increase to ~32GW by 2027



Assumptions:
7.5% p.a. load growth.
No delays in non-VRE capacity addition.
90 GW new solar + 10 GW new wind.

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Summary: Storage requirement by 2027 to avoid shortages

	Formula	Demand growth = 6% p.a.	Demand growth = 7.5% p.a.	Demand growth = 10% p.a.
Net Addition to the Evening Peak	C = B-A	45	57	77
New Firm Capacity (as scheduled)	D	41	41	41
Net Firm Capacity Shortfall	E = C-D	**4**	**16**	**36**
New RE Capacity Needed by 2027	F	100	100	135
Storage Requirement to avoid shortages	**G**	***4 GW 4 GWh***	***16 GW 62 GWh***	***32 GW 180 GWh***

Note: All numbers in GW. This is a simplistic exercise for developing an intuitive understanding. An implicit assumption behind this simplistic calculation is that the maximum firm capacity support by the existing generation capacity cannot go beyond 2024 summer levels (~221 GW). Also, RE generation is not given any evening peak capacity credit. Finally, all new hydro capacity, including ROR plants have been generously given full capacity credit. No delays are assumed in commissioning the under-construction power plants.

If firm capacity addition is delayed, potential shortages could start as early as 2025

	Formula	Demand growth = 6% p.a.	Demand growth = 7.5% p.a.	Demand growth = 10% p.a.
Net Addition to the Evening Peak	C = B-A	45	57	77
New Firm Capacity (1-yr delay)	D	28	28	28
Net Firm Capacity Shortfall	E = C-D	**17**	**29**	**49**
New RE Capacity Needed by 2027	F	100	120	165
Storage Requirement to avoid shortages	**G**	***17 GW 17 GWh***	***27 GW 78 GWh***	***43 GW 243 GWh***

Note: All numbers in GW. This is a simplistic exercise for developing an intuitive understanding. An implicit assumption behind this simplistic calculation is that the maximum firm capacity support by the existing generation capacity cannot go beyond 2024 summer levels (~221 GW). Also, RE generation is not given any evening peak capacity credit. Finally, all new hydro capacity, including ROR plants have been generously given full capacity credit.

3. Solar + Storage is highly economical

Surging Interest in Battery Storage: Competitive Bidding from Major Developers in Recent Large Scale Auctions

- Recent battery storage auctions have received an overwhelmingly positive response, with multiple major developers, including JSW Neo, NTPC Renewables, Renew Power etc bidding aggressively
- In each auction, there have been at least 5-6 developers that bid within 5% of the winning bid, indicating the winning bids are not outliers

GUVNL bid for 250 MW/500MWh double cycling standalone storage, March 2024

Winning bid = Rs 448,996/MW-month or Rs 4.6/kWh

S#	Bidder's Name	Quoted Value	Loaded Value	Currency	Date/Time of Bidding	Bidder's Quantity	% Difference greater than Rank-1 Bid Value
1	Gensol Engineering Limited	448996.00	448996.00	Indian Rupee	06-Mar-2024 22:23:30 RTZ	70.00	0%
2	IndiGrid 2 Limited	449996.00	449996.00	Indian Rupee	06-Mar-2024 22:20:20 RTZ	250.00	0.22%
3	JSW Neo Energy Limited	449997.00	449997.00	Indian Rupee	06-Mar-2024 22:19:49 RTZ	250.00	0.22%
4	Hero Solar Energy Private Limited	538000.00	538000.00	Indian Rupee	06-Mar-2024 17:06:00 RTZ	70.00	19.82%
5	NTPC Renewable Energy Limited	949999.00	949999.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	100.00	111.58%
6	ACME Solar Holdings Private Limited	990000.00	990000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	120.49%
7	SJVN Green Energy Limited	991000.00	991000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	120.71%
8	VENT RENEWABLES PRIVATE LIMITED	995000.00	995000.00	Indian Rupee	06-Mar-2024 13:03:15 RTZ	70.00	121.61%

Note: Quoted Values are in Rs/MW-month, Bidders Quantity in MW of storage

GUVNL bid for 250 MW/500MWh double cycling standalone storage, June 2024

Winning bid = Rs 372,978/MW-month or Rs 3.8/kWh

S#	Bidder's Name	Quoted Value	Loaded Value	Date/ Time of Bidding	Bidder's Quantity	Special Remarks	Difference in % (Bid-Value vs Start-Price)
1	Gensol Engineering Limited (ETS-IN-2019-RS0000329)	372978.00	372978.00	11-Jun-2024 18:59:34 RTZ	250.00	Field Not Filled	20.81%
2	IndiGrid 2 Limited (ETS-IN-2023-RS0000456)	372978.00	372978.00	11-Jun-2024 19:04:43 RTZ	250.00	Field Not Filled	20.81%
3	JSW Neo Energy Limited (ETS-IN-2021-RS0000180)	373979.00	373979.00	11-Jun-2024 18:53:06 RTZ	250.00	Field Not Filled	20.60%
4	PACE DIGITEK INFRA PVT LTD (ETS-IN-2024-RS0000210)	375900.00	375900.00	11-Jun-2024 18:31:55 RTZ	100.00	Field Not Filled	20.19%
5	CONTINENTAL MILKOSE (INDIA) LIMITED (ETS-IN-2023-RS0000579)	383000.00	383000.00	11-Jun-2024 18:39:11 RTZ	70.00	Field Not Filled	18.68%
6	ACME Solar Holdings Private Limited (ETS-IN-2019-RS0000080)	383983.00	383983.00	11-Jun-2024 18:08:58 RTZ	250.00	Field Not Filled	18.47%
7	JBM RENEWABLES PRIVATE LIMITED (ETS-IN-2020-RS0000188)	420500.00	420500.00	11-Jun-2024 16:30:37 RTZ	250.00	Field Not Filled	10.72%
8	HINDUJA RENEWABLES ENERGY PRIVATE LIMITED (ETS-IN-2021-RS0000181)	466000.00	466000.00	11-Jun-2024 15:28:37 RTZ	130.00	Field Not Filled	1.06%
9	VIKRAM SOLAR CLEANTECH PRIVATE LIMITED (ETS-IN-2019-RS0000333)	542000.00	542000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-15.07%
10	Apraava Energy Private Limited (ETS-IN-2022-RS0000031)	600000.00	600000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-27.39%
11	NTPC Renewable Energy Limited (ETS-IN-2021-RS0000051)	662000.00	662000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-40.55%
12	SOLARCRAFT POWER INDIA 12 PRIVATE LIMITED (ETS-IN-2024-RS0000054)	766000.00	766000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-62.63%
13	SJVN Green Energy Limited (ETS-IN-2022-RS0000261)	795000.00	795000.00	11-Jun-2024 13:14:05 RTZ	70.00	Field Not Filled	-68.79%

Note: Quoted Values are in Rs/MW-month, Bidders Quantity in MW of storage

SECI 1200 MW + 600 MW/1200 MWh co-located battery storage, July 2024

Winning bid = Rs 3.41/kWh (solar+storage)

S#	Bidder's Name	Quoted Value	Loaded Value	Currency	Date/Time of Bidding	Bidder's Quantity	% Difference greater than Rank-1 Bid Value
1	PACE DIGITEK INFRA PVT LTD	3.41	3.41	Indian Rupee	16-Jul-2024 17:55:47 RTZ	100.00	0%
2	Hero Solar Energy Private Limited	3.42	3.42	Indian Rupee	16-Jul-2024 17:54:31 RTZ	250.00	0.29%
3	ACME Solar Holdings Limited	3.42	3.42	Indian Rupee	16-Jul-2024 17:54:35 RTZ	350.00	0.29%
4	JSW Neo Energy Limited	3.42	3.42	Indian Rupee	16-Jul-2024 17:54:53 RTZ	600.00	0.29%
5	NTPC Renewable Energy Limited	3.43	3.43	Indian Rupee	16-Jul-2024 17:36:52 RTZ	300.00	0.59%
6	Solarcraft Power India 8 Pvt Ltd	3.50	3.50	Indian Rupee	16-Jul-2024 17:07:37 RTZ	150.00	2.64%
7	Rays Power Infra Limited	3.50	3.50	Indian Rupee	16-Jul-2024 17:08:53 RTZ	100.00	2.64%
8	Hexa Climate Solutions Private Limited	3.67	3.67	Indian Rupee	16-Jul-2024 15:38:37 RTZ	200.00	7.62%
9	ReNew Solar Power Private Limited	3.71	3.71	Indian Rupee	16-Jul-2024 15:19:43 RTZ	300.00	8.80%

Note: Quoted Values are in Rs/kWh, Bidders Quantity in MW of solar

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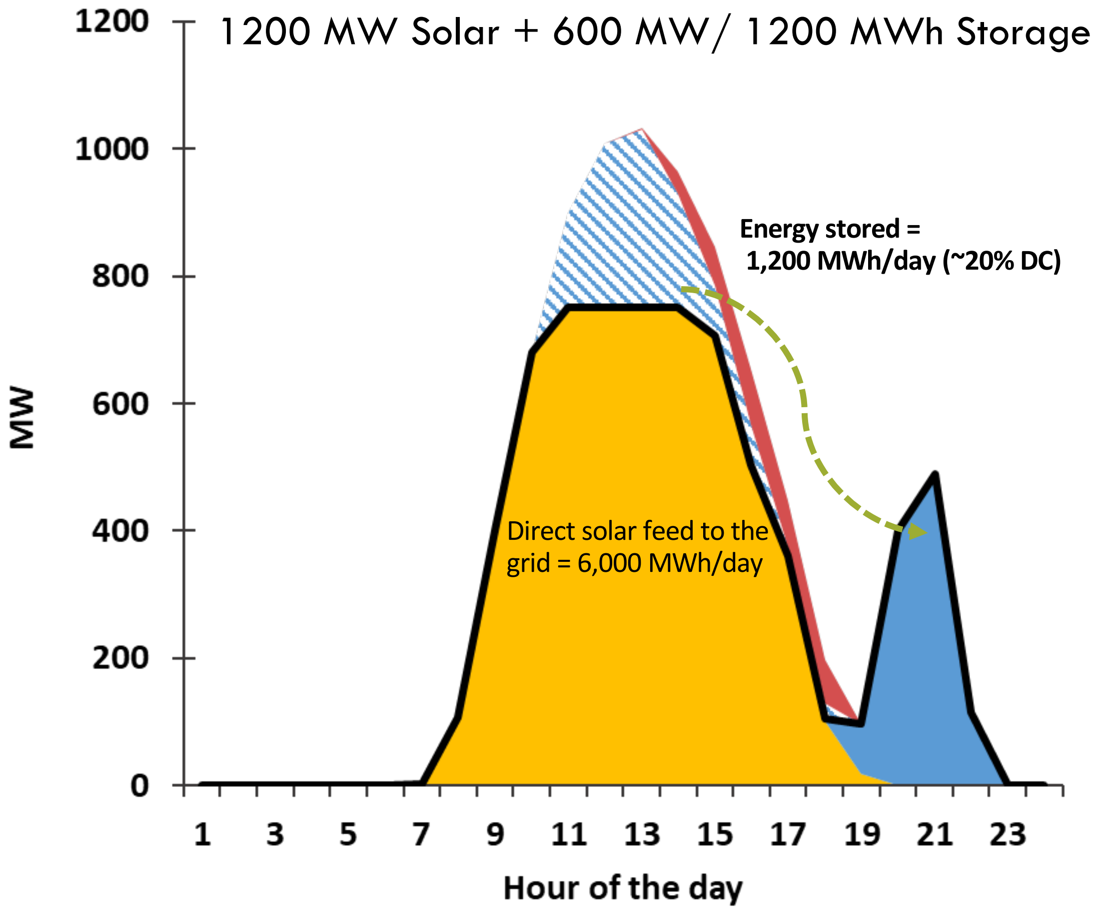
India's storage moment: Why SECI solar + storage auction results are so important ?



SECI's 1200 MW solar + 600 MW/1200 MWh storage (~15% AC and 20% DC solar energy stored in batteries) auction price was Rs 3.41/kWh.

- SECI conducted 1200 MW solar + co-located 600 MW/1200 MWh battery storage auctions in July 2024.
- The winning bid was ₹ 3.41/kWh, which indicates a dramatic reduction in battery storage cost.
- Assuming a solar LCOE of ₹ 2.6/kWh, this implies an **evening peak storage adder of ₹ 0.81/kWh**
- **This implies a battery storage capital cost of $150/kWh** (Assumptions: storage availability = 95%, round trip efficiency = 90%, and annual cycles = 365 cycles/yr)
- With 4-hr batteries, the storage adder drops further

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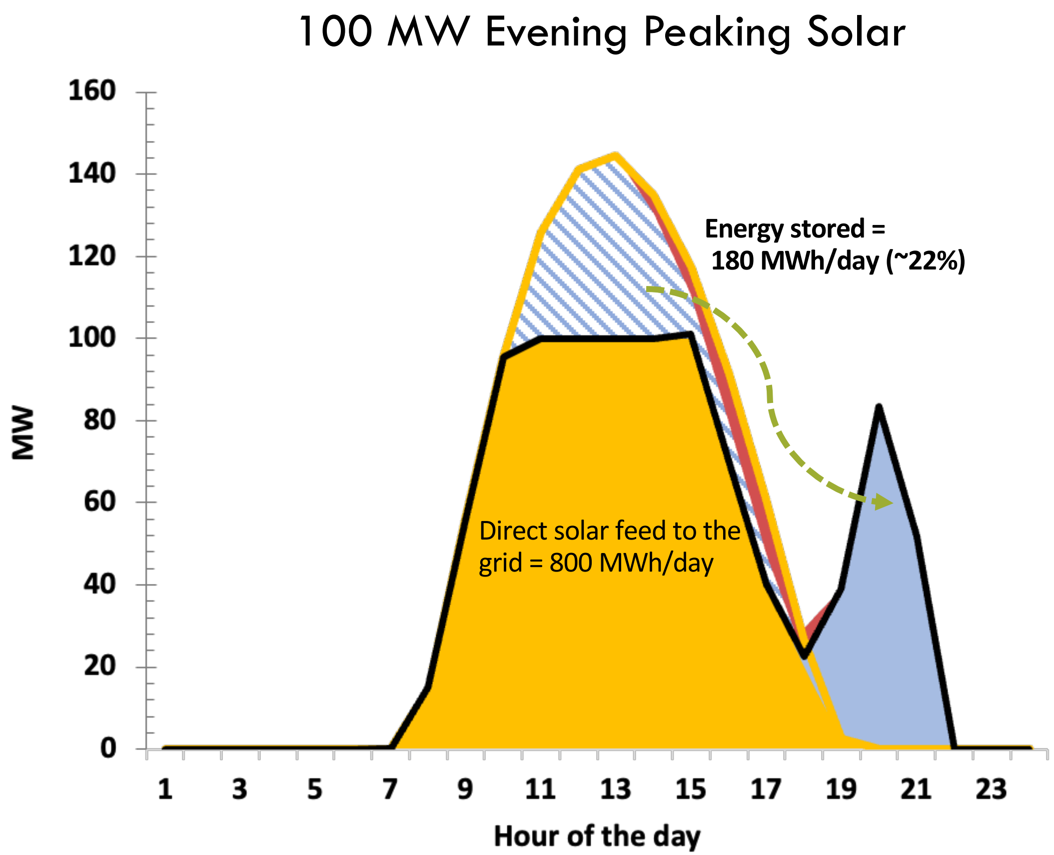
GUVNL's standalone storage auction results in June 2024 point to similar costs



Evening peaking solar + storage requires ~ 22% of DC solar energy to be stored

- GUVNL latest bid: ₹3.73 lakh per MW per month, for 250 MW/500 MWh battery for 2 cycles/day (June 2024 auction).
- **This implies a standalone storage capital cost of $200/kWh.**
- This implies the **cost of standalone storage = ₹3.8/kWh for two cycles/day or 730 cycles/yr** (₹3.73 lakh divided by 120 MWh throughput in a month, adjusted for 85% roundtrip efficiency and 95% availability)
- **2-hour evening peaking storage adder = ₹1.2 - 1.5/kWh**
- For one cycle/day (~365 cycles/yr), the cost of standalone storage = **₹6.5/kWh**
- With 4-hr batteries or co-location, the storage adder drops further

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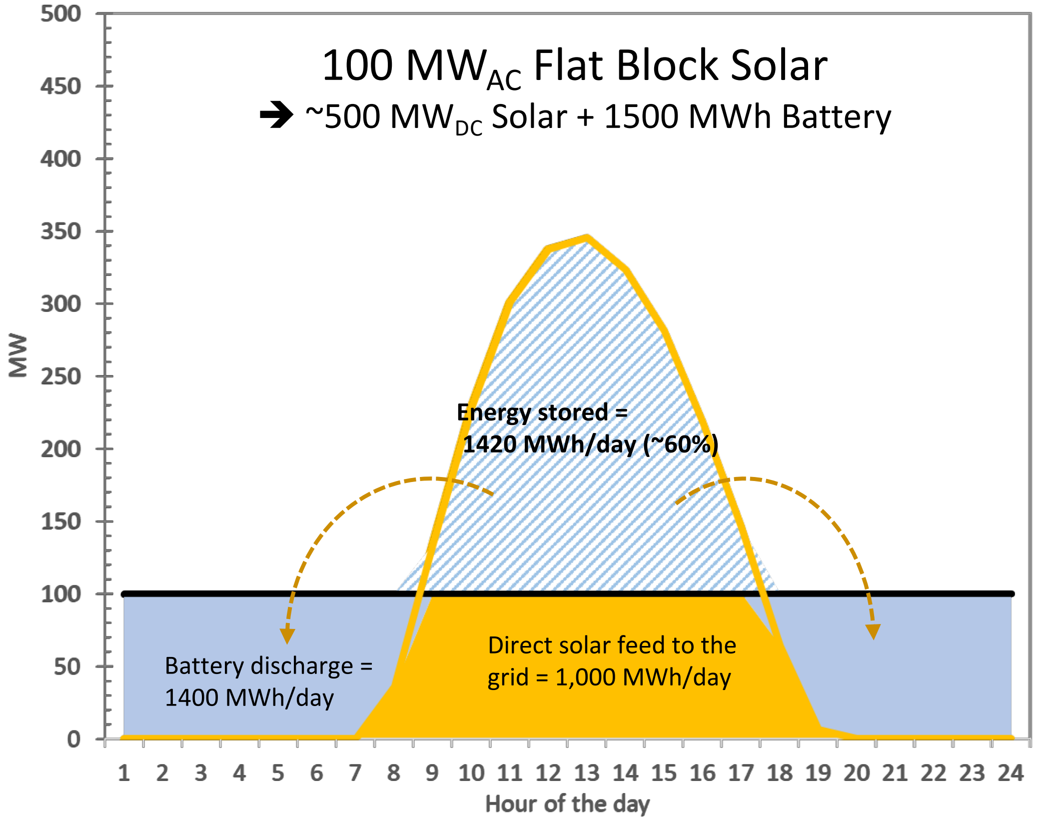
Economics of flat-block solar+storage looks very promising



Flat block of solar + storage requires ~ 60% of the solar energy to be stored

- Flat block solar + storage requires ~60% of DC solar energy to be stored
- @ SECI storage adder of ₹ 0.81/kWh for 20% DC solar energy stored, storage adder for 60% DC solar energy storage would be ~3 times.

  ➔ **Storage adder for flat-block = ~₹ 2.5/kWh**

  ➔ **Flat block solar + storage = 2.6 + 2.5 = ~₹ 5.1/kWh**

- These numbers are also evidenced by GUVNL standalone storage auction results
- Given the global trends in the batteries market, the storage adder may further reduce by 25% by 2030
  ➔ **solar + storage flat block @ Rs ~4.5/kWh**

  ➔ **New thermal investments need to be seriously reassessed**

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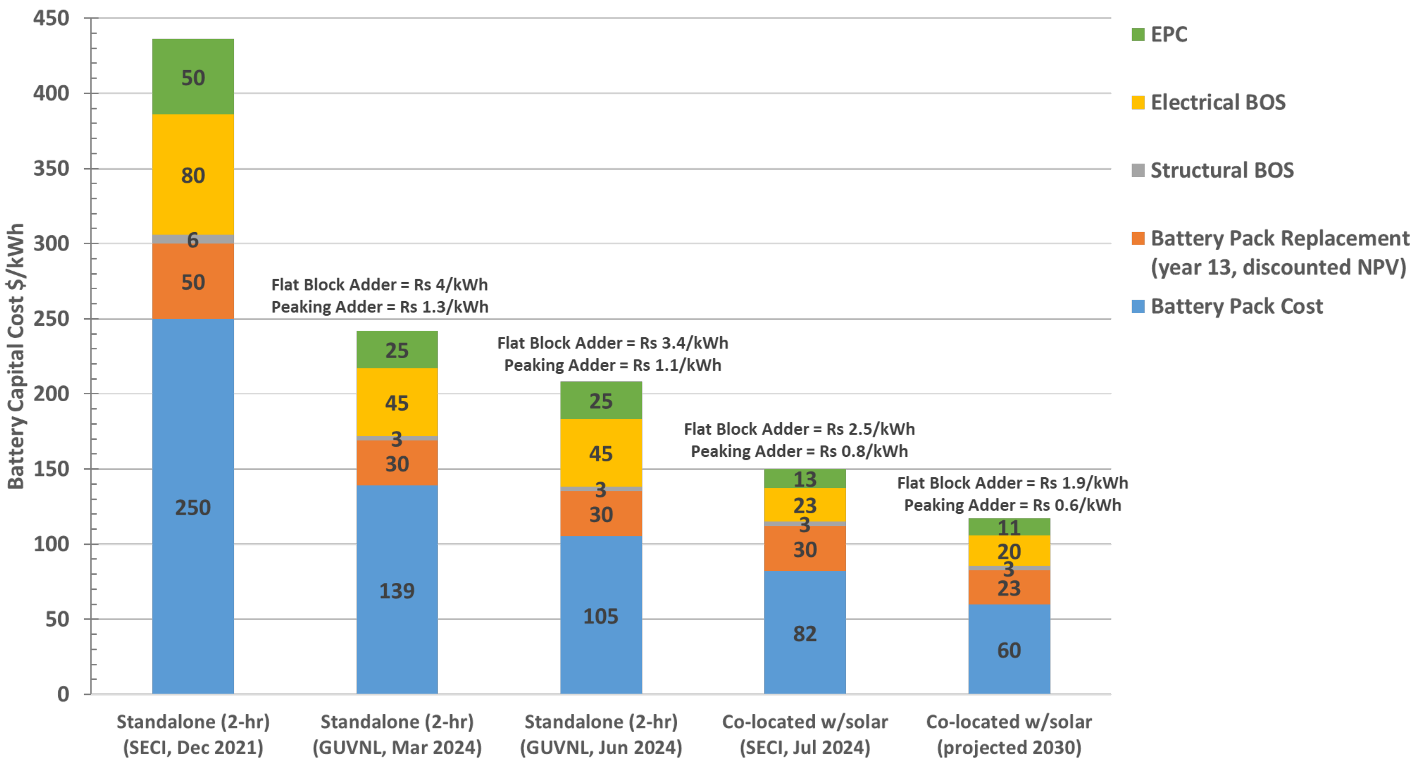
Co-located battery storage capital cost has already fallen to ~$150/kWh and will likely drop further by ~15-20% by 2030

The chart shows estimated battery capital costs split into key components (reverse engineered from winning bids and other market data)



- Over the last 2-3 years, battery storage prices have seen a dramatic reduction in India with standalone battery storage capital cost estimated at ~$200/kWh and co-located battery storage capital cost estimated at ~$150/kWh.
- Co-location of batteries with solar offers significant BOS cost savings, reducing the overall capital cost by ~20%.
- As of July 2024, based on the auction results, evening peaking storage adder on top of RE LCOE would be Rs 1.2/kWh, which drops to Rs 0.8/kWh with co-location with solar.
- By 2030, it is likely that these costs would drop further by 15-20%, indicating a significant shift in how India should plan future power sector investments.

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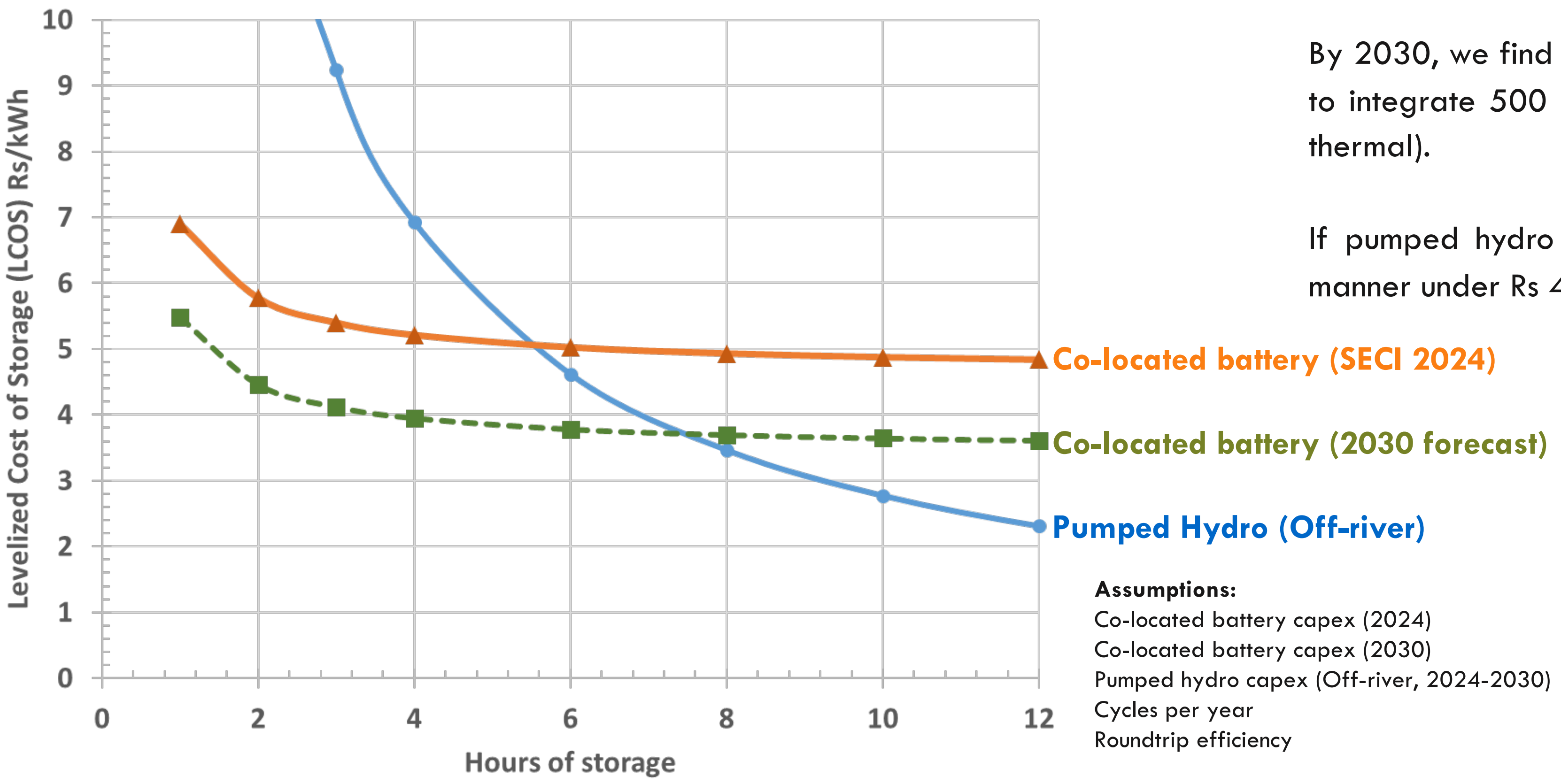
Pumped Hydro or Battery Storage ?

Batteries are energy (MWh) constrained, while pumped hydro resources are power (MW) constrained.
For low storage hours, batteries are cheaper

Single-cycle levelized cost of storage



For up to 6-8 hours/day of storage, battery storage is more economical (already economical up to 5-6 hours/day).

By 2030, we find that India will need 4-6 hours of energy storage to integrate 500 GW of clean power (along with ~240 GW of thermal).

If pumped hydro projects could be developed in a time bound manner under Rs 4 Cr/MW, they should be encouraged.

Assumptions:

Co-located battery capex (2024)	= $150/kWh for 2 hours per SECI bids
Co-located battery capex (2030)	= $120/kWh for 2 hours (authors' projections)
Pumped hydro capex (Off-river, 2024-2030)	= Rs 4.5 Cr/MW
Cycles per year	= 300
Roundtrip efficiency	= 80% (PHS); 90% (BESS)

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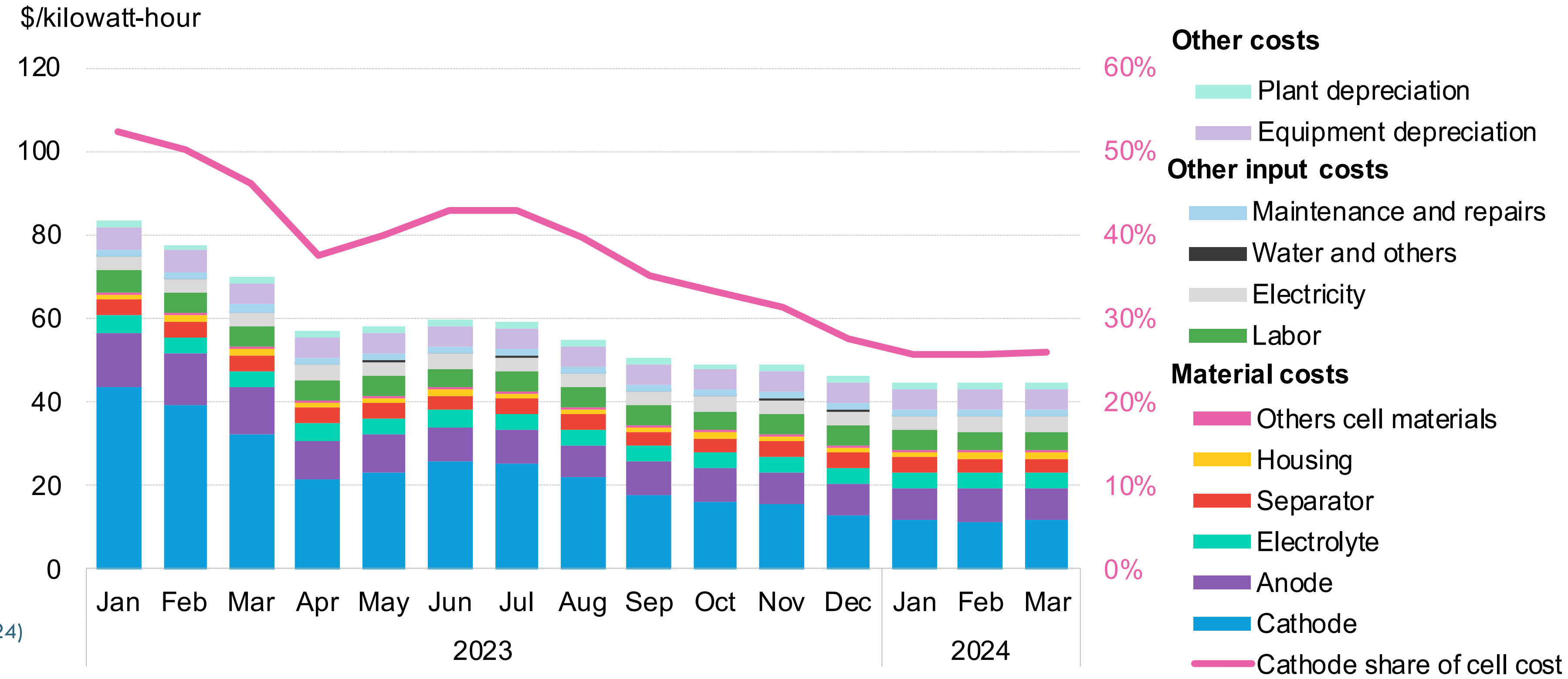
Declining material costs and overcapacity are driving dramatic decline in storage costs

Lithium iron phosphate (LFP) battery cell manufacturing costs by component and cathode share of cell cost



Source: BNEF (2024)

Source: BloombergNEF, ICC Battery. Note: The cost breakdown uses BNEF's BattMan Cost Model to calculate the production cost of a 120Ah lithium iron phosphate (LFP) and artificial graphite prismatic cell produced in a 10-gigawatt-hour LFP battery cell plant located in China. Cathode costs are adjusted using the cathode spot price from ICC Battery.

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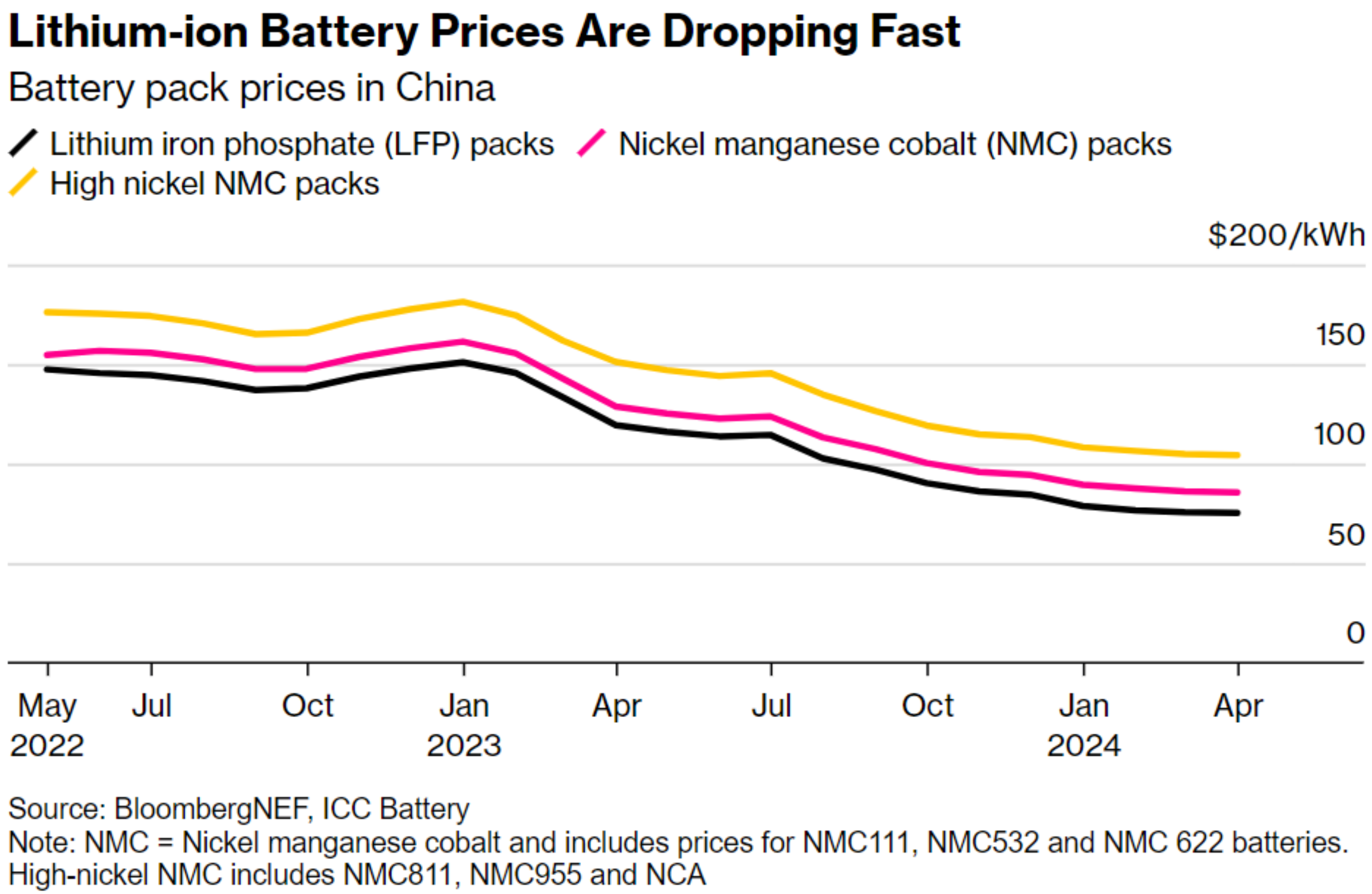
In China, LFP pack prices have already fallen to $75/kWh

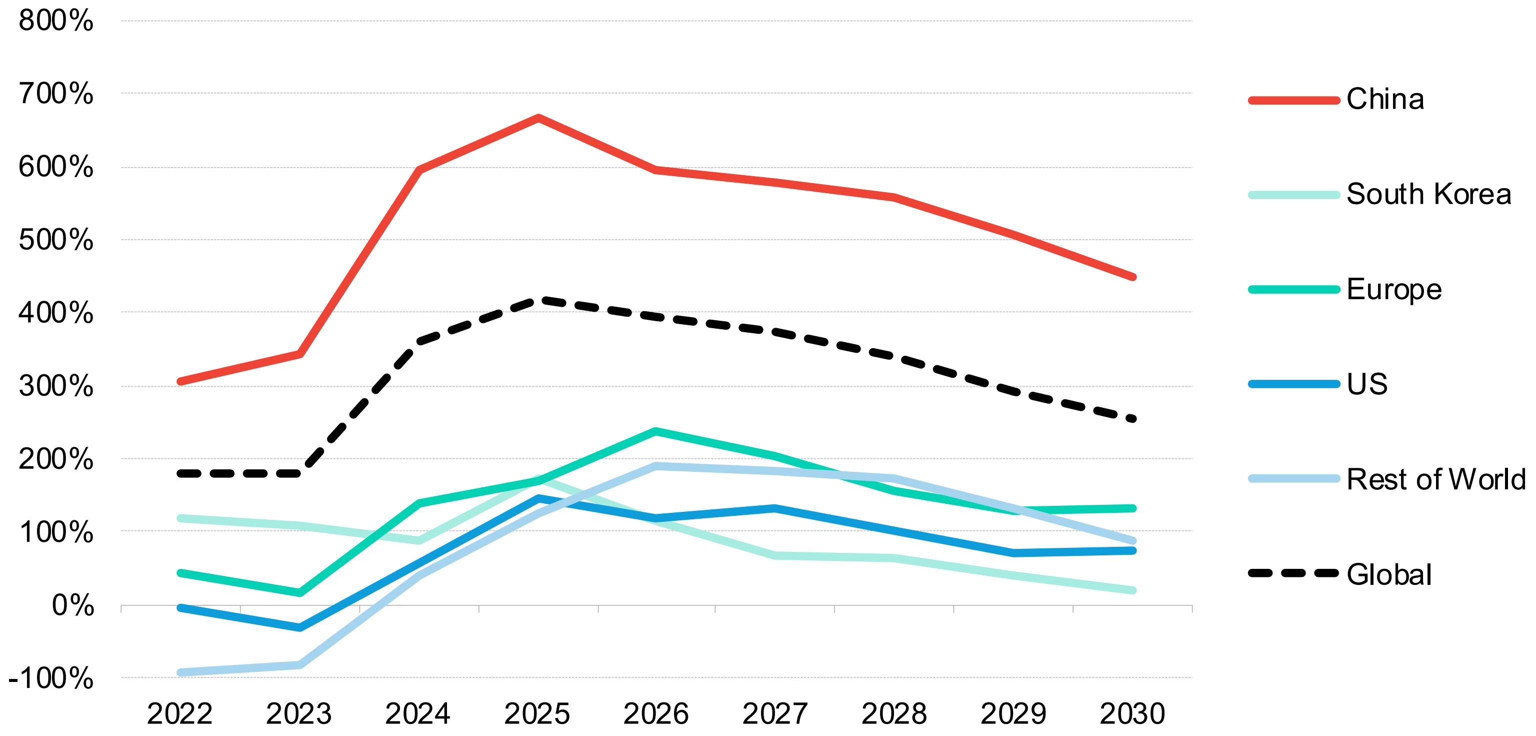


Source: BNEF (2024)

Pack-level prices for the most-sold battery chemistries have been below the often-referenced $100/kWh benchmark in China since October 2023, and LFP pack prices are now at $75/kWh.

Lithium-ion battery cell manufacturing overcapacity will persist at least until 2030 (~ total capacity of 5000 GWh/year in China)

Lithium-ion battery cell manufacturing overcapacity ratio from 2022 to 2030



Source: BNEF (2024)

Source: BloombergNEF. Note: Overcapacity ratio based on the manufacturing capacity over the same year's demand. Demand is based on BNEF's EVO 2024. Nameplate manufacturing capacity as of May 9, 2024. Includes plants that are fully owned by battery makers, as well as joint ventures with automakers, however, pack assembly plants are excluded. 2023 manufacturing capacity includes only fully commissioned capacity. Future capacity is based on non-de-risked capacity tracked by BNEF's battery manufacturing database based on commissioning date before December 31 of respective years.

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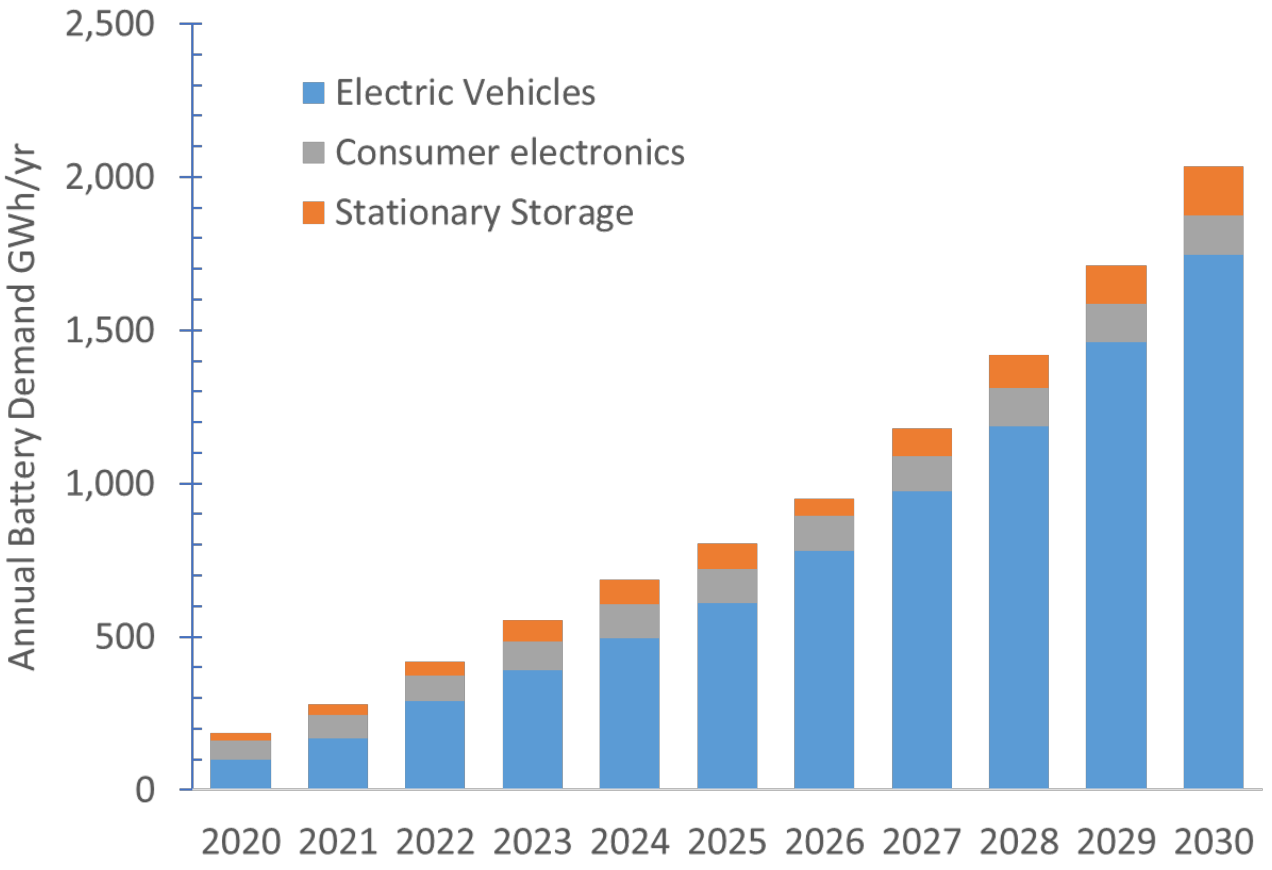
Battery supply chains will be dominated by the auto sector



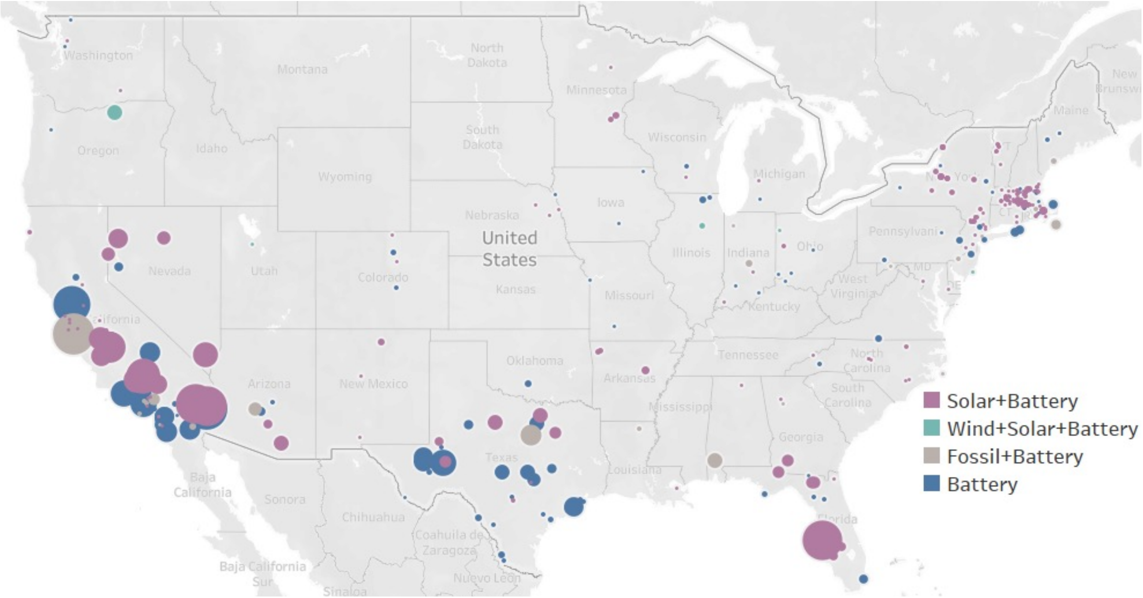
Data Sources: BNEF (2023); DOE (2021); Statista (2023)

- One of the key concerns around battery storage is about battery supply chains and energy security.
- It is important to understand that EV battery demand is ~10 times that of stationary storage, implying power sector is unlikely to strain supply chains.
- Moreover, major Indian auto manufacturers such as Tata and Mahindra are manufacturing EVs in India and have secured battery supply chains.
- Additionally, over 100 GWh of battery manufacturing capacity is current in planning or under construction.

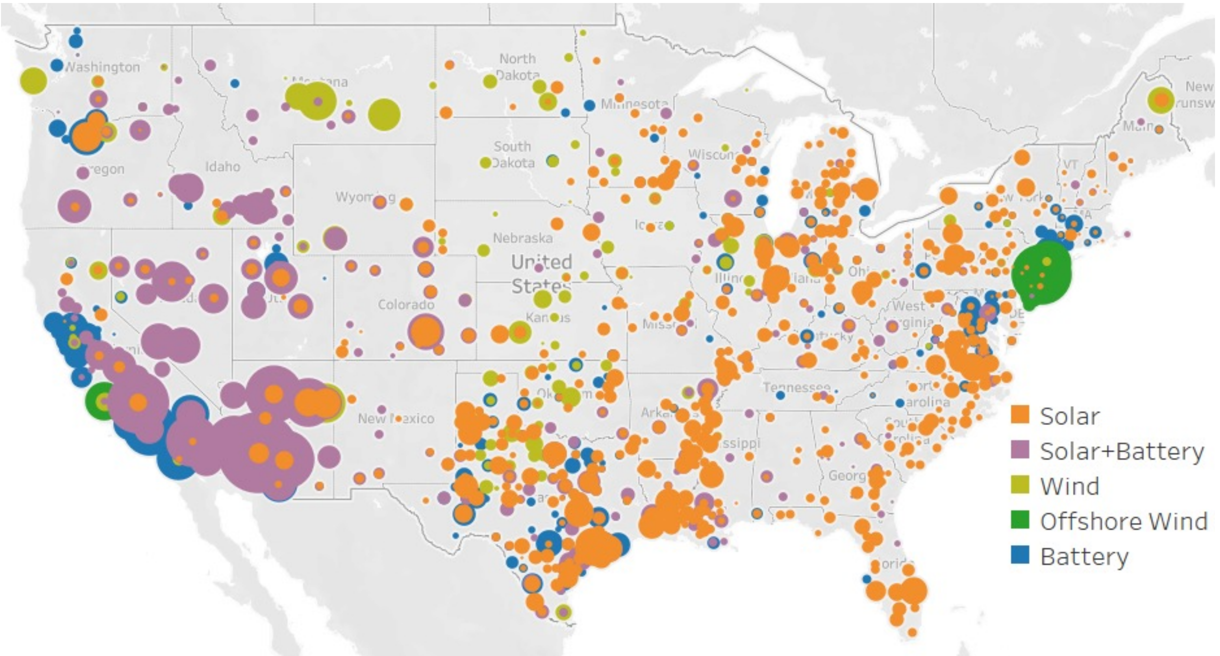
Deep storage cost declines is dramatically impacting resource choices in the US

US existing battery installations:
~15 GW with nearly half in California
Typical duration is 2-4 hours
~50% is co-located with solar, while 40% is standalone

US interconnection queue (i.e. RE pipeline) includes:
~1100 GW Solar **(incl ~500GW solar + storage)**
~350 GW Wind
~500 GW of Standalone Batteries



Data Sources: EIA (2023); Bolinger et al (2023)

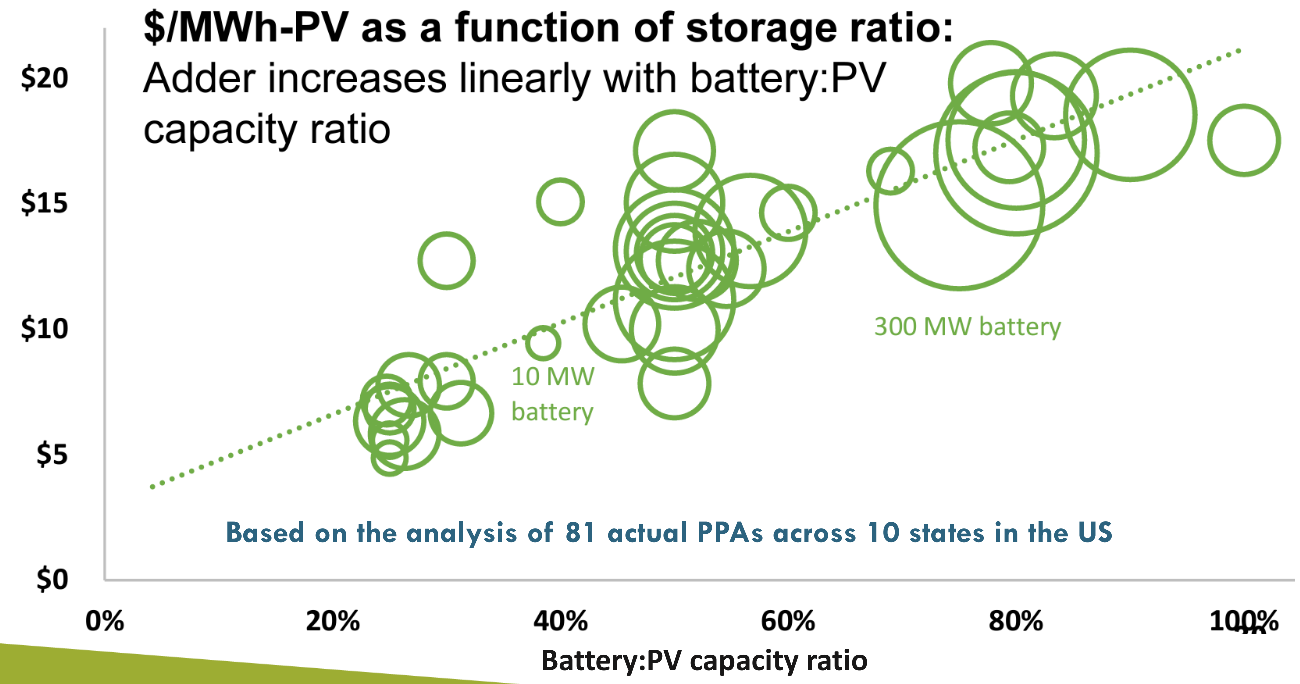


Data Source: Rand et al (2024)

4-hour storage adds modest costs (~$12/MWh) to solar PPAs in the US

Low battery costs and co-location benefits

Typical configuration in the US
50% of PV MW x 4 hours
(~20-30% of daily solar generation)
Average storage cost adder = $12/MWh (Rs 1/kWh)



Source: Bolinger et al (2023)

Solar + storage PPA prices (subsidized)
~$30-40/MWh or Rs ~2.5-3/kWh
(unsubsidized costs ~25-30% higher)

State	Plant Name	Solar (MW)	BESS (MWh)	Solar+BESS PPA price ($/MWh)	Date
CA	RE_Slate_SVCE/ CCCE	161	321	32.9	Feb-20
NV	Chuckwalla	200	720	36.4	Mar-20
NV	Boulder_3	128	232	28.9	Apr-20
CA	Arlington_Energy Center_II	233	528	35.1	Oct-20
NV	Hot_Pot	350	1120	35.3	Jun-21
NV	Iron_Point	250	800	36.9	Jun-21

Data Source: Bolinger et al (2023)

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4. Policy support needed to ensure fast deployment at scale

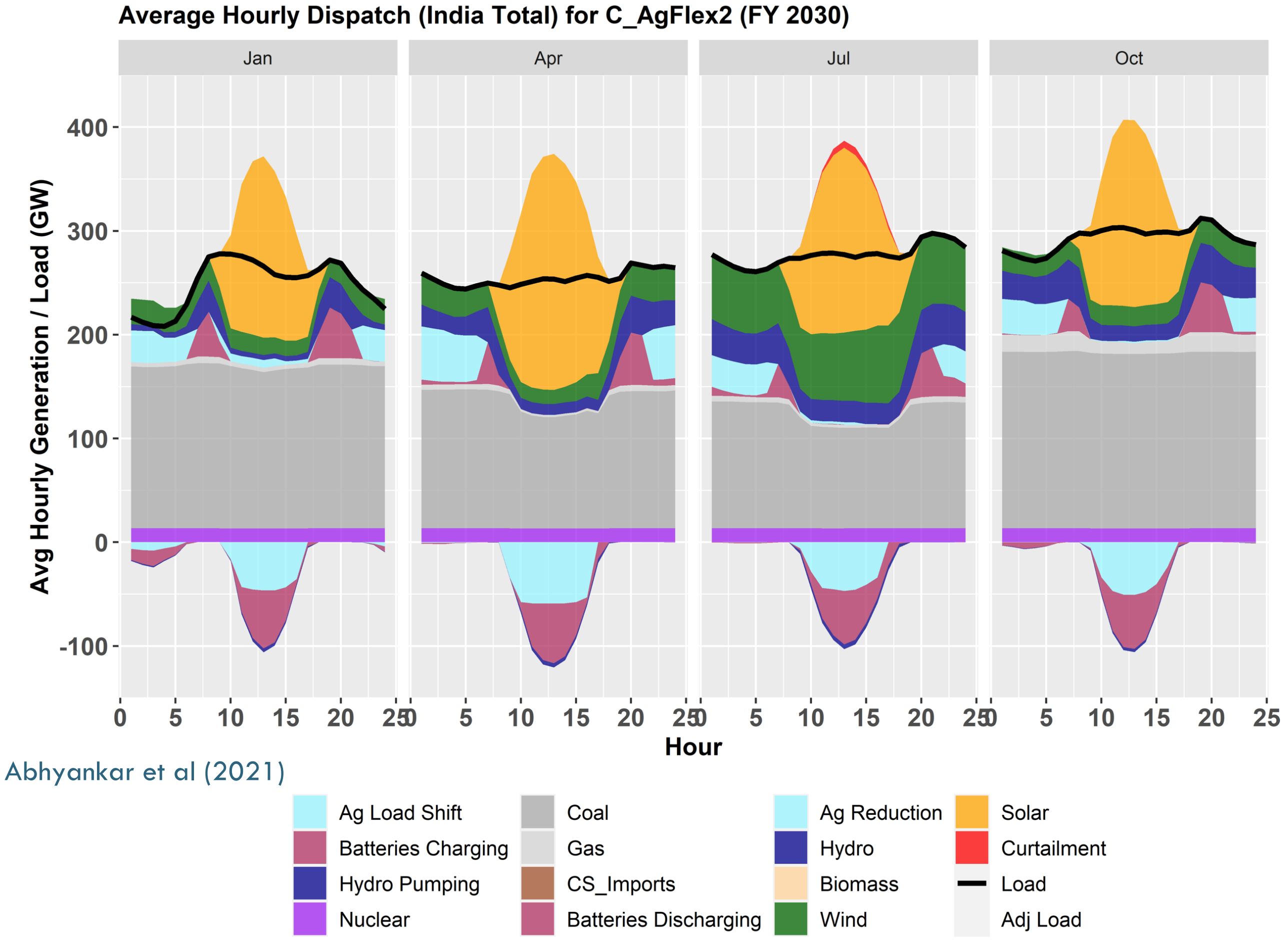
Policy and Regulatory Strategies: Near Term Recommendations

- **Large-scale solar + co-located storage auctions (~15-20 GW/yr)**
  - Evening peaking RE would be critical for increasing deployment by states
  - Can work in tandem with technology neutral procurement obligation (just like RPS) for utilities
  - Achieve solar + storage cost target of Rs 3/kWh by 2027; SECI (2024) auctions already at Rs 3.41/kWh
- **Require all new solar / RE capacity to have co-located storage**
  - Require energy storage of ~25-30% by capacity x 4 hours (equivalent to ~15-20% of diurnal energy storage)
  - Co-location can reduce storage capital cost by 15-20%
- **Offer VGF on solar + co-located storage LCOE above say Rs 3.0/kWh**
  - Approximate requirement to avoid shortages = 50-100 GW Solar + 16-32 GW storage x 4 hrs
  - Approximate VGF requirement to avoid shortages = Rs 4,000 – 10,000 Cr/yr
- **Capture the full storage value chain**
  - Avoiding inefficient thermal investments, energy arbitrage, ancillary services etc.

5. Significant RE and storage expansion in the long-run

By 2030, with ~240 GW Coal capacity, India will be baseload sufficient but peak-deficit ➔ 4-6 hours of storage most-optimal

National dispatch in FY 2030 with 500 GW clean power



Source: Abhyankar et al (2021)

What role does storage play ?
Critical source of flexibility & diurnal balancing. Avoids inefficient thermal investments and enhances transmission asset utilization

How much storage is required ?
By 2030, ~250-300 GWh of energy storage will be optimal (~10-15% avg daily RE generation)

How is the storage operated ?
Charged once during the day, discharged during the morning and evening peak (*4-6 hours/day*).
➔ **One charge-discharge cycle in a day**

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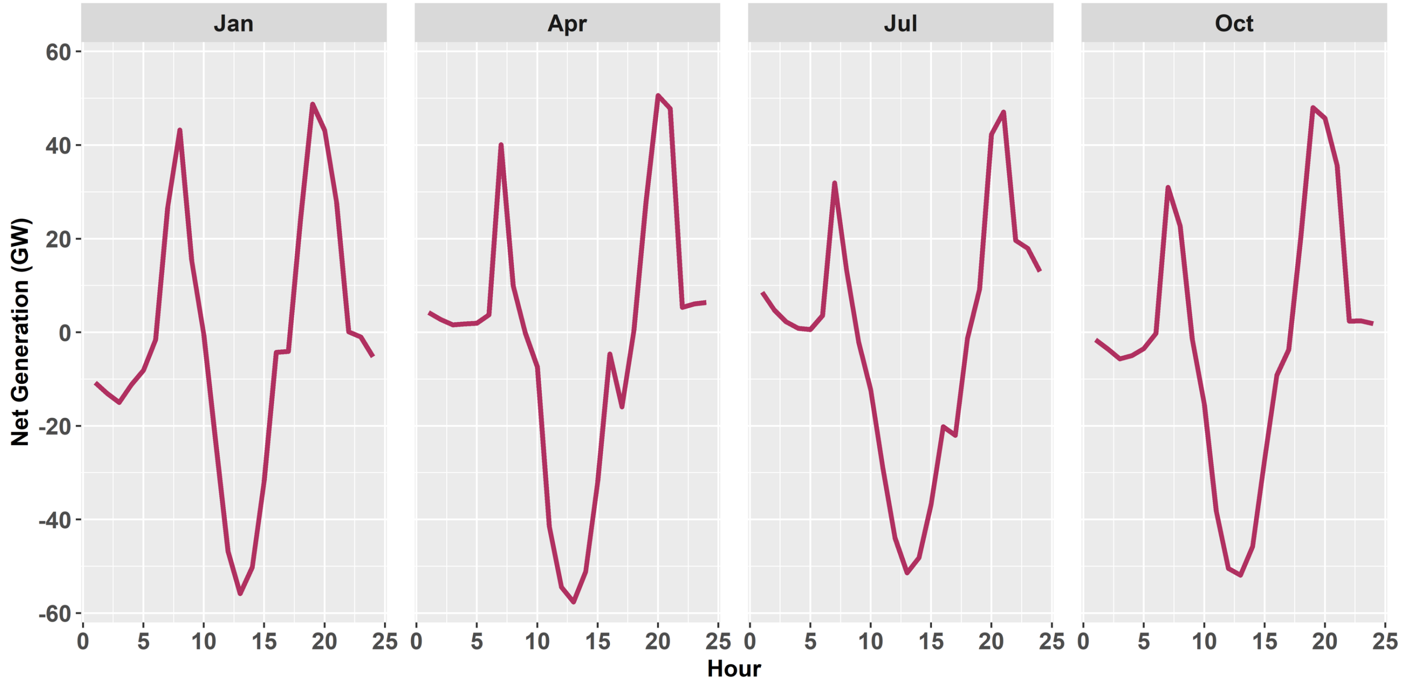
How much storage will be required by 2030 and how will it be operated?

Average charge (negative) and discharge (positive) operation of energy storage in FY 2030 for supporting 500 GW clean power



Source: Abhyankar et al (2021)

Optimal energy storage requirement (All-India)

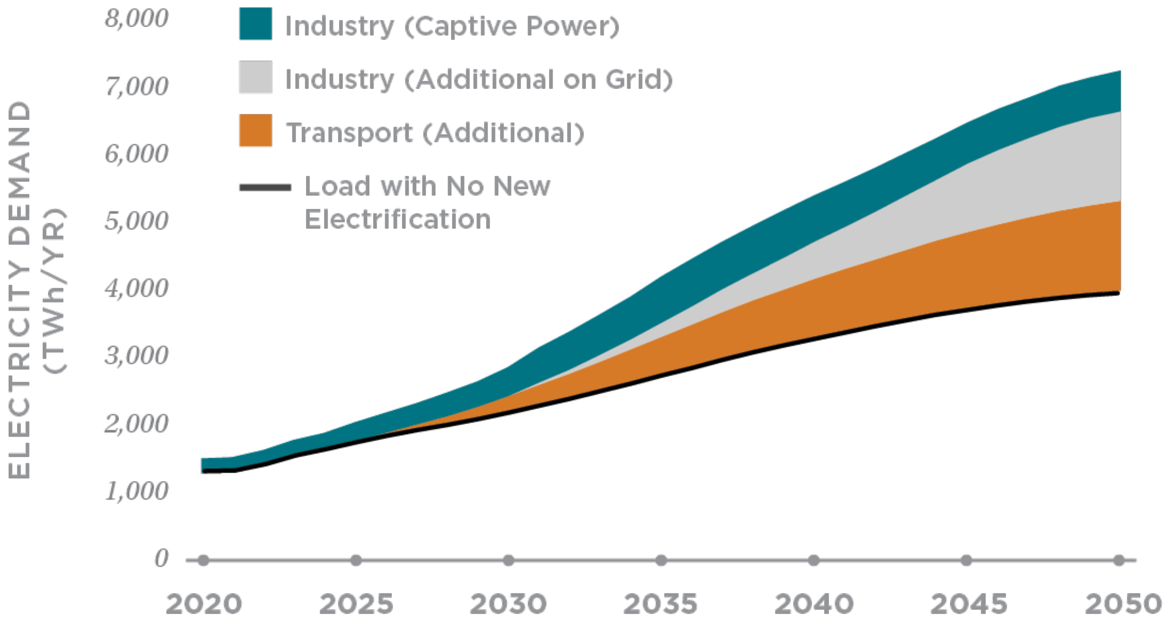
2025	2030
12 GW/ 52 GWh	67 GW/ 254 GWh

Typically, just one full charge-discharge cycle in a day.

Charge during solar hours & discharge during evening & morning peak hours (4-6 hrs/day).

Electric vehicles, green hydrogen, industrial electrification, and AI-driven data centers imply a five-fold increase in electricity demand by 2050

Additional Electrification in the CLEAN Pathway



In the CLEAN India case transport and industrial electrification as well as green hydrogen production would increase the electricity demand five-fold by 2050:

- From 1500 TWh in 2022 to 3000 TWh by 2030 and 7200 TWh by 2050, including industrial captive power.

This load growth will be 6-7% p.a on average.

Compared to the Reference case, we estimate the net additional investment required for the CLEAN pathway is $1.5-2 trillion (INR 11-15 million crores).

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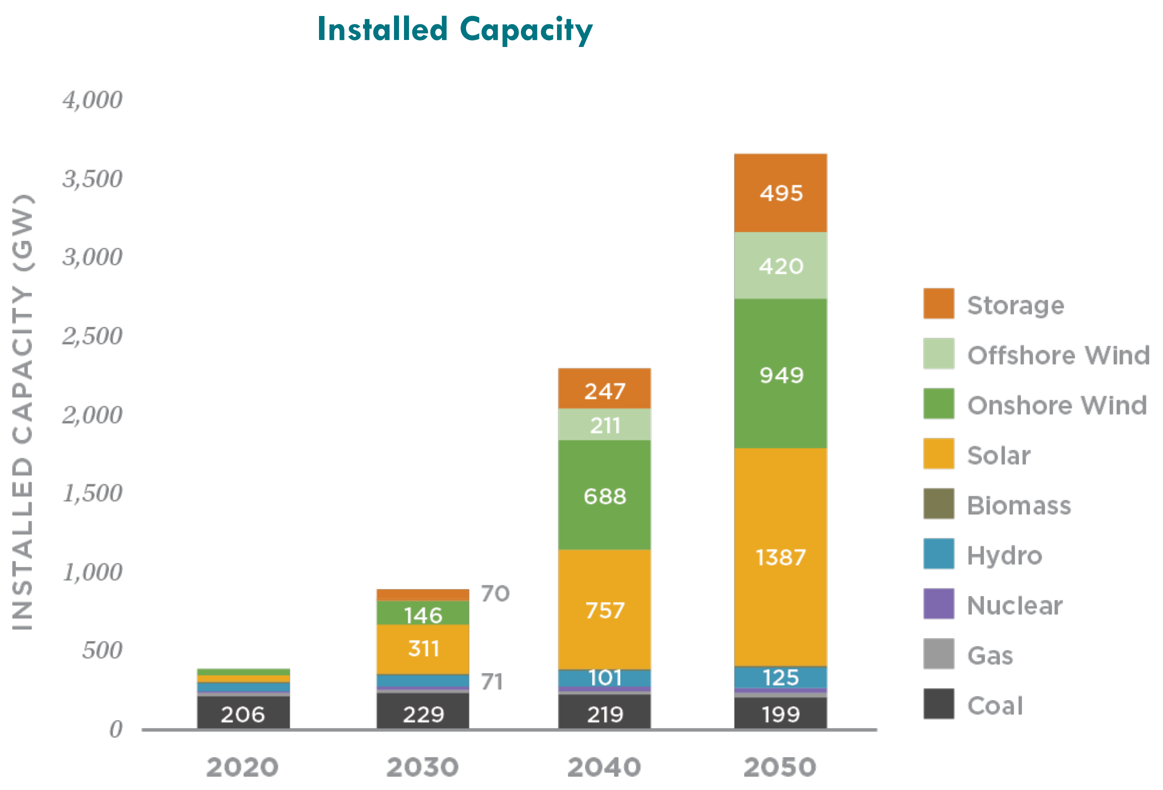
End-use electrification + a clean power grid would require massive RE scale-up



- **Thermal investments:**
  - Continue with the coal power plants that are already under construction. (2030 coal capacity = ~230GW)
  - But no new coal/gas power plant beyond 2027/2028.

- **Non-Fossil capacity:**
  - ~500 GW total by 2030
  - ~1800 GW total by 2040
  - ~2800 GW total by 2050
  - Offshore wind resources (400GW by 2050) will be critical for rapid and cost-effective RE expansion.

- **Storage:** Energy storage capacity of ~60-70GW (~250 GWh) by 2030 and ~500GW (~2500 GWh) by 2050

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Appendix

Storage investment requirement and storage cost adder

- At $150/kWh, 62 GWh (16 GW) will cost $9.3 billion, and at $100/kWh, it will cost $6.2 billion
  - 16 GW of firm thermal capacity will cost $16 billion, although can not be compared directly.

- The per-unit storage cost is approximately Rs 4.5/kWh
  - ($150/kWh * capital recovery factor of 13%) / (360 cycles per year) = $19/360 = Rs 4.5/kWh.

- Co-location of storage with solar offers several benefits, including BOS (Balance of System) cost savings, transmission cost savings, and increasing the value of solar to the utility.

- If storage is co-located with solar and its cost is added to the cost of solar, it will increase the solar capex and LCOE by ~35%
  - Assuming 50 GW solar + 62 GWh storage: Solar capex = $25 billion, storage capex = $9 billion, raising the LCOE from Rs 2.5/kWh to ~ Rs 3.5/kWh, and at $100/kWh to Rs. 3.1/kWh.

How much VGF would storage need to avoid shortages in India?

	Demand growth = 6%	Demand growth = 7.5%	Demand growth = 10%
Storage Requirement to avoid shortages	4 GW 4 GWh	16 GW 62 GWh	32 GW 140 GWh
Solar capacity for storage co-location	4 GW	50 GW	100 GW
Solar LCOE Rs/kWh	2.5	2.5	2.5
Storage Cost Adder Rs/kWh	0.6	1.0	1.1
Solar + Storage LCOE Rs/kWh	3.1	3.5	3.6
VGF above Rs 3.0/kWh	**0.1**	**0.5**	**0.6**
Total VGF to avoid shortages Rs Cr/yr	**100**	**4,000**	**10,000**
Fixed cost of new thermal to avoid shortages Rs Cr/yr	**4,700**	**19,000**	**38,000**

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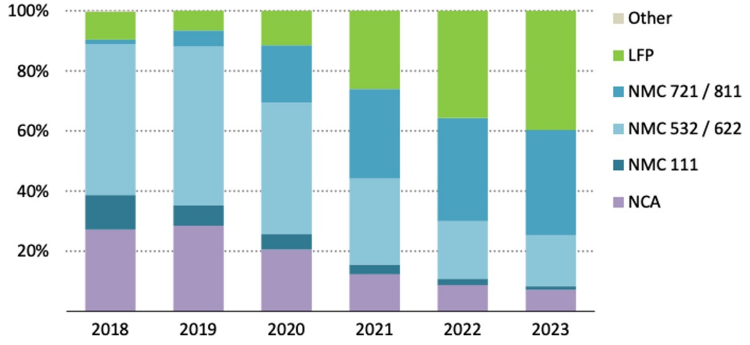
While costs have come down, battery technology has improved significantly

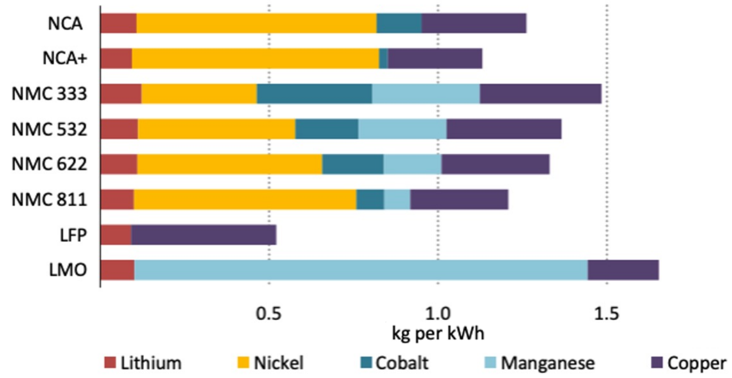
Lithium Ion Phosphate (LFP) batteries have rapidly grown in market share in EV sales, over conventional Nickel Manganese Cobalt (NMC) chemistries:

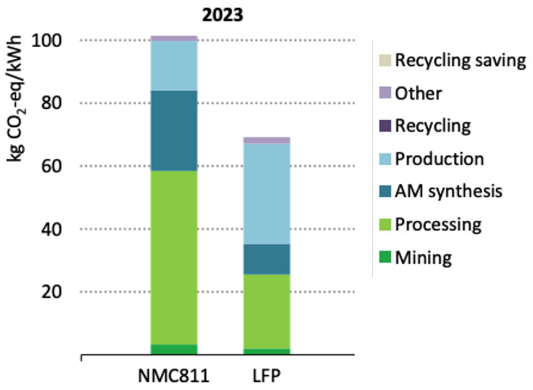


IEA (2024)

This is largely driven by LFP's lower cost (-20% less than NMC) and higher cycle life, prompting Chinese battery manufacturers and major EV makers like Tesla alike to increasingly favor LFP

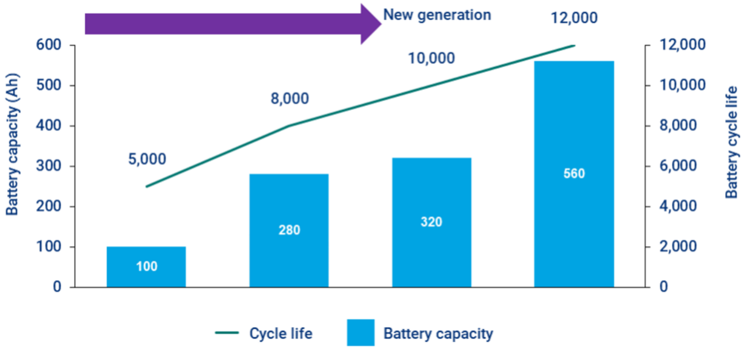
LFP cathodes require significantly less critical minerals than NMC varieties, and have lower emissions:





IEA (2024)

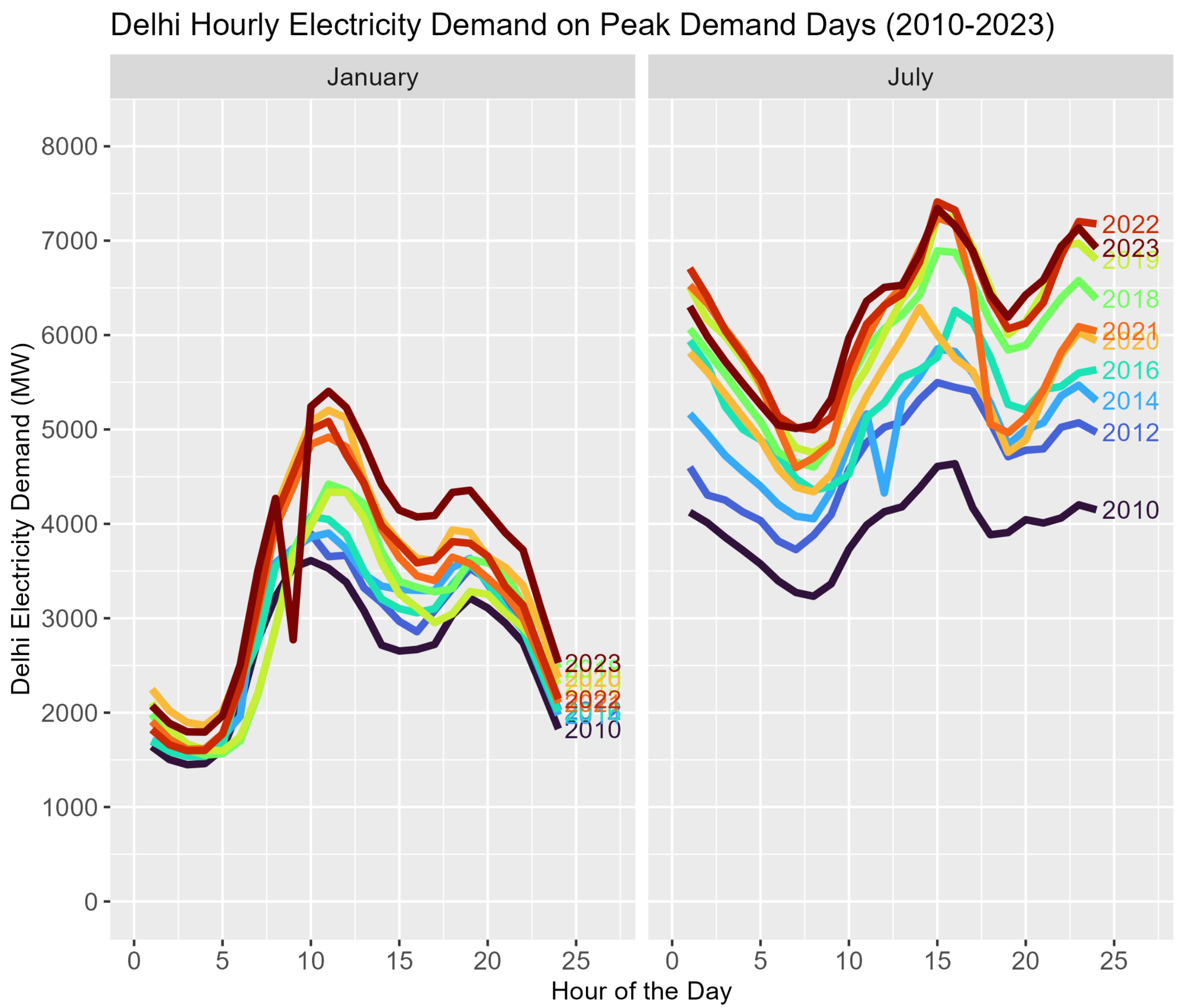
NMC cells have higher energy densities (+20% more than LFP), yet LFP energy densities have improved in recent



Wood Mackenzie (2023)

While the high energy densities offered by NMC batteries are relevant for long-range EVs as well as heavy duty applications like trucks, **grid-scale battery storage** will likely increasingly leverage low-cost LFP batteries, led by China

Space cooling demand is one of the key contributors to the rising peak demand



The importance of space cooling load in rising electricity demand could be seen more prominently in certain urban centers like Delhi. Over the past decade, Delhi's electricity consumption has nearly doubled, overcoming all COVID-related slowdowns. Notably, the summer peak in July has surged, surpassing the winter peak and indicating a rapid increase in space cooling appliances. The summer demand now exhibits two distinct peaks: one at 3 PM, driven by commercial space cooling, and another at midnight, driven by residential space cooling. Similar trends are already observed / expected in other urban centers, albeit in different months.

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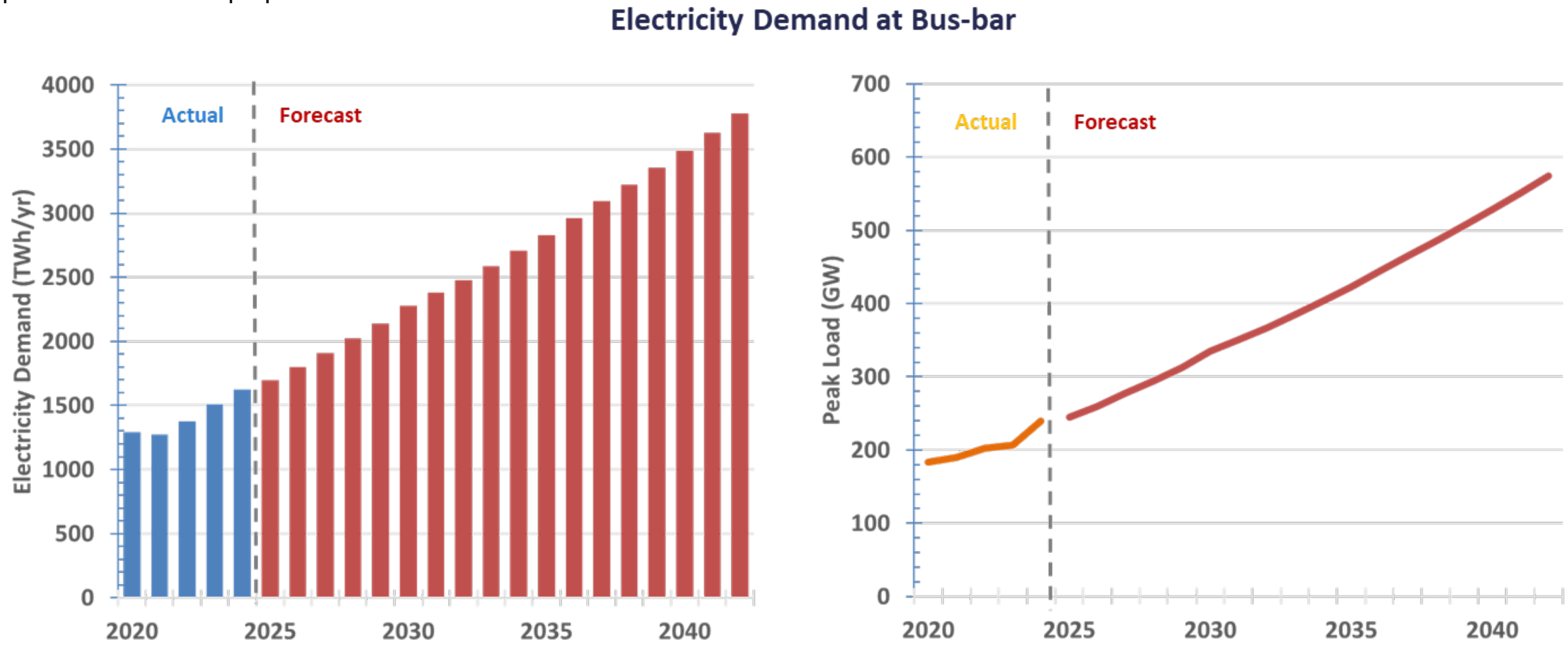
India’s peak demand will cross 340 GW by 2027 and 400 GW by 2035

India’s electricity demand is projected to continue its robust upward trajectory. By 2030, peak demand is expected to surge by around 90 GW from current levels, reaching approximately 340 GW. This represents an annual growth rate of 6-7%, which is significantly higher than the global average. The 20th Electric Power Survey (EPS) projects that India's electricity demand will continue to grow at a similar pace through 2042, putting immense pressure on the country's power sector to keep up.



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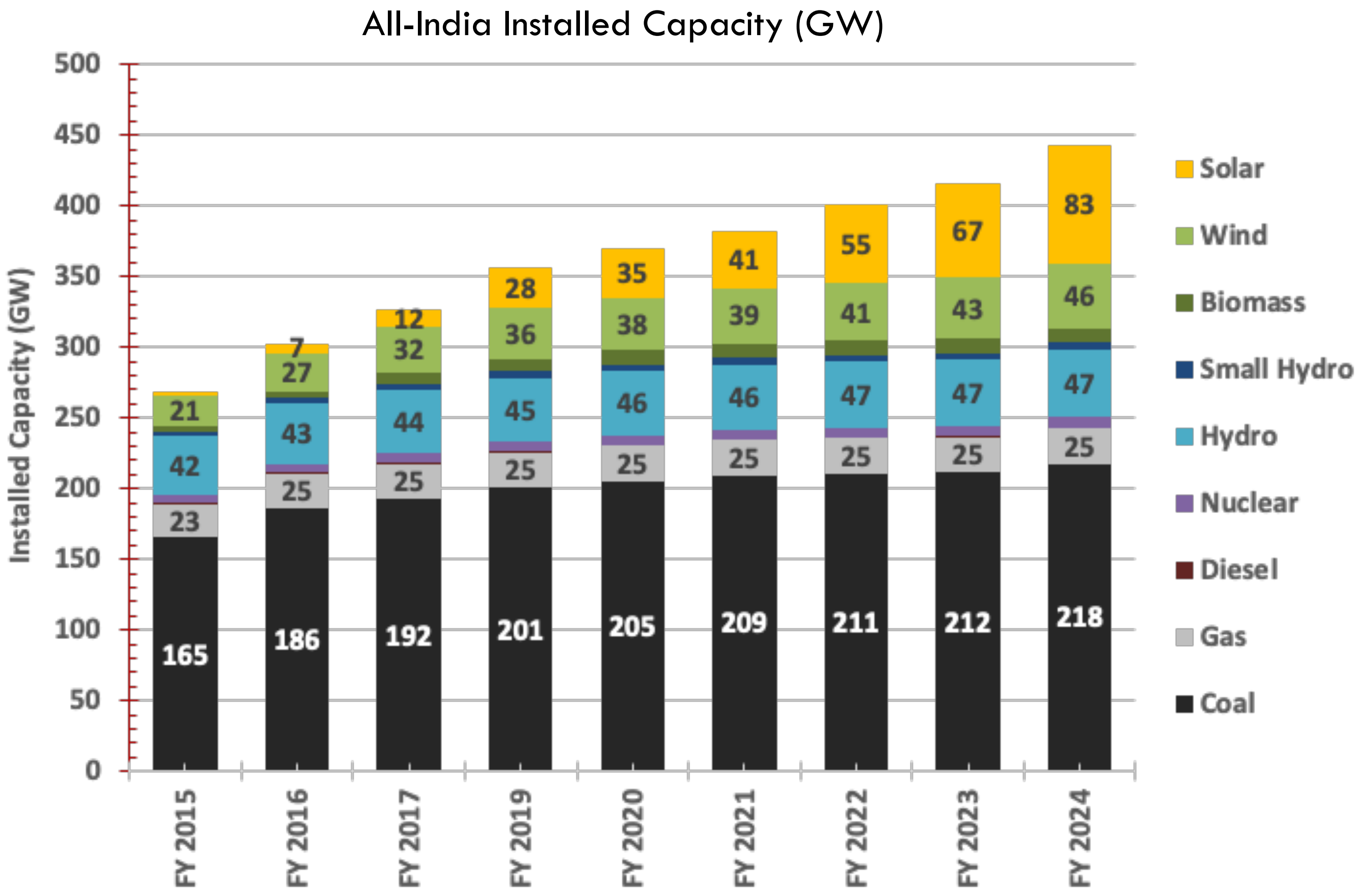
Between 2015 & 2024, India added 175 GW to its power generation capacity with RE contributing ~65% of this growth



Over the past nine years (FY 2015-2024), India has added a substantial 175 GW to its power generation capacity. This growth includes approximately 52 GW from coal and over 113 GW from renewable energy (RE) sources. Notably, between FY 2020 and FY 2024, India saw the addition of 48 GW of solar capacity and over 8 GW of wind capacity.

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Evening Peaks and Solar Dips: Wholesale Energy Price Trends on IEX

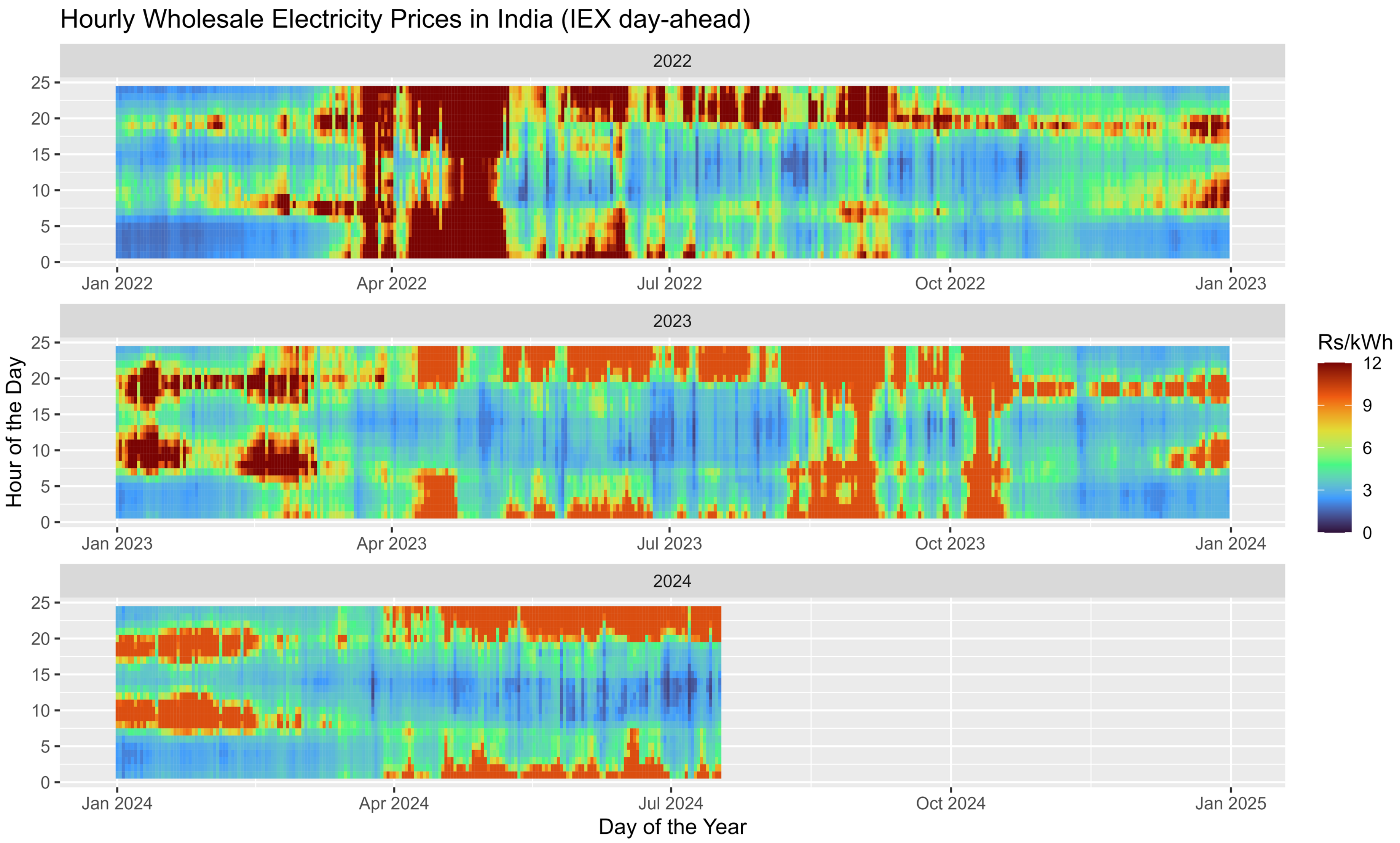
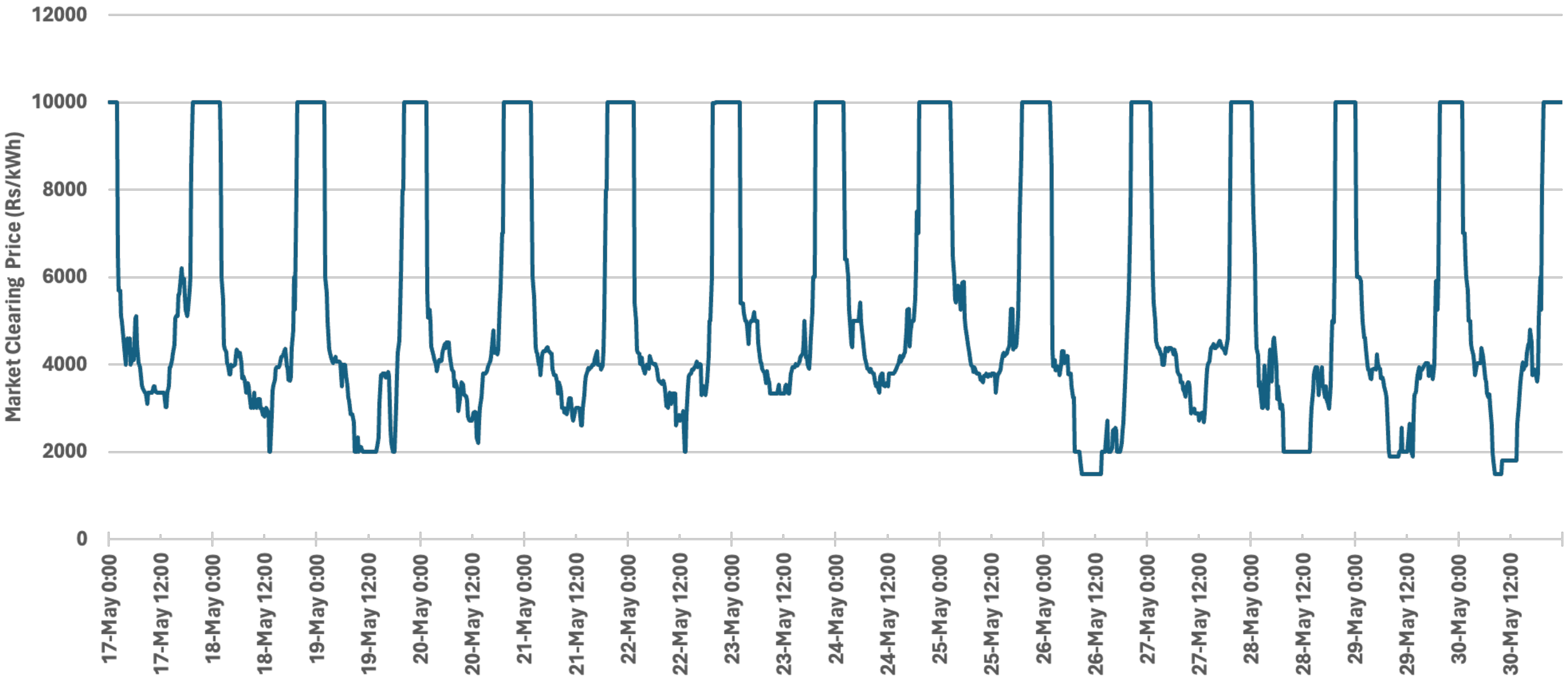


Chart shows day ahead wholesale energy prices on Indian Energy Exchange for the previous three years. X-axis is the day of the year (365 days from Jan 1 through Dec 31) and the Y-Axis is the hour of the day (1 to 24). Color of each grid point shows the electricity price, which changes every 15-minutes. Blue is low price, red is high price, as shown on the color scale.

Even during recent heatwave events, IEX prices drop during solar hrs & hit the ceiling for 4-6 hours at night (starting ~7 PM)



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