Granular Time of Day Analysis of Balancing the Indian Electricity Grid in 2030

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Model and Analysis

- India has very aggressive plans for scaling RE (450 GW by 2030; today is 100 GW)
- Using 2019 time of day (ToD) data for both demand and supply by fuel type, what happens over time (2021-2030) for the system (national level) under different assumptions of rising RE?
  - Will the RE be enough to avoid new coal?
  - Will there be a risk of "too much" RE (that might be curtailed)?
  - What will be least cost options for the system?
  - How should we think of batteries?
  - What are the key choices and points of uncertainty that matter?
  - *etc.*
- This is a simplified despatch model but using real 2019 ToD data all-India
- The focus is on insights and trends – and what factors matter

Balancing the grid: A complex real-time challenge

- The AC Electricity grid must always be in real time balance between supply and demand (inclusive of losses)
  - Storage is yet limited
- Electricity used to be designed around sufficient supply to meet varying demand
  - Now, even supply is variable, based on RE (Renewable Energy)
- Different fuel mixes interplay to provide sufficient supply (to avoid load-shedding)

SUPPLY	Despatchable (firm) power?	Fixed Cost	Variable Cost	Ramping (varying output) capabilities
Coal	YES	HIGH	LOW to MEDIUM	MEDIUM
Gas	YES	MEDIUM OR LOW	HIGH	HIGH
Nuclear	YES	VERY HIGH	LOW	~ZERO
Hydro	YES	HIGH	~ZERO	VERY HIGH
RE (without battery)	NO (use-it-or-lose-it)	MEDIUM	ZERO	n.a.

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2019 carbontracker data

5-minute resolution

Source: Underlying Data from MERIT India

Created using support from Shakti Sustainable Energy Foundation

Literature and other studies

- Grid studies span characteristics incl:
  - Timeline (2022 or 2030)
  - Some assume RE output
    - Measured data are limited
  - Supply can be plant *unit* level or aggregated, or clustered
  - Transmission can be internalized or left exogenous
    - Can assume "perfect transmission"
  - Typical analyses are hourly system
    - Some are part of year if higher resolution

- Other models
  - Greening The Grid (GTG)
    - First was 2022 focused for 175 GW RE
  - Prayas & CSTEP
    - State-centric
  - TERI
    - 2030, assume cost of battery as a "fuel"
  - Shayak Sengupta et. al
    - Reduced form
  - Puneet Chitkara et. al
    - GAMS optimization

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Unique features of this study/model

- Parametric analysis with 30-minute resolution
- Future RE is modeled VERY differently and explicitly
  - Different shapes of outputs
  - Different shares of wind vs. solar
- Segregate capacity and energy for battery
  - Most studies assume "4-hour battery", i.e., $200/kWh = 0.25 kW output for 4 hours
  - Some studies use LCOE for battery operating like a fuel
- Use varying escalation rates across capital, fuel, forex, interest, etc. (thus, not a simple LCOE)

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General observations of “today” (2019+)

- There is surplus capacity in the day
- The peak is shifting to mid-day, but “net demand” remains in the evening
- Coal dominates supply
  - Some capacity may retire
  - Some capacity (if not all) should get FGD (pollution control) equipment – impacts outputs

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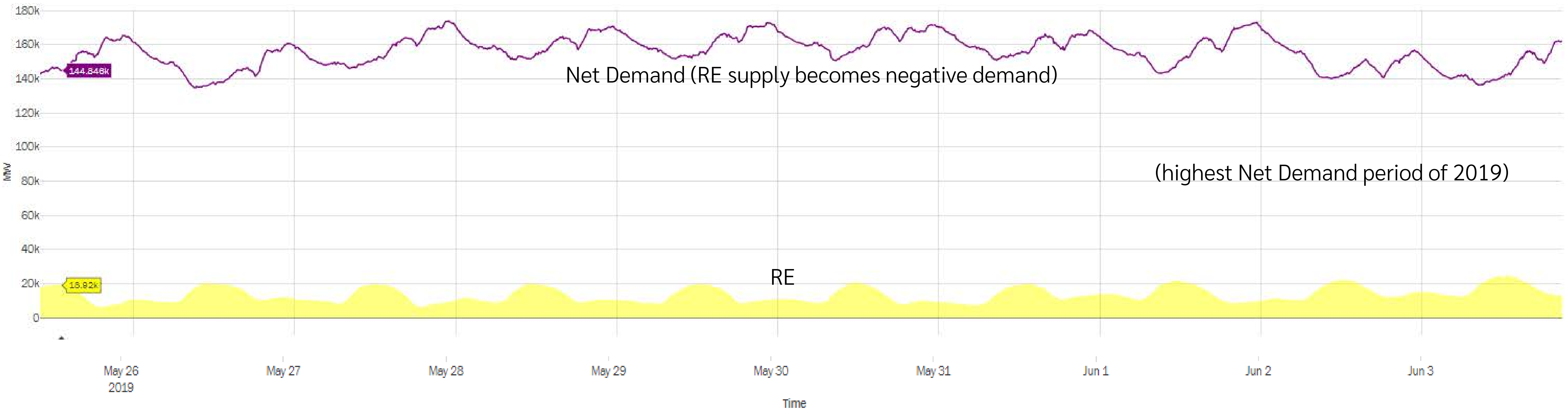
“Net Demand” (= minus RE) maxes in the evening



- Solar creates the daily RE shape curve
- Rising solar will reduce the mid-day net demand = “duck curve”

(tracker as shown under-captures RE – we correct for that as best possible in the analysis)

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All RE isn't the same

- Solar and wind dominate, esp. the growth – 450 GW target by 2030 could be 420 GW solar and wind (per CEA, also projects 2:1 ratio)
- Solar is diurnal variance, less seasonal variance than wind
  - But wind provides more output during evening peak
- Solar is less expensive on an levelized cost of energy (LCOE) basis
  - Solar has a lower Capacity Utilization Factor aka Plant Load Factor than wind
    - New growth may be 27% and 36+%, respectively
      - That excludes rooftop, which remains low PLFs (and is "negative demand")
- Big Unknown – shape of RE growth over the years (CAGR, linear, etc.)?
  - Model assumes exponential/CAGR
    - Practical but it also reflects today's reality in energy terms:

      Growth of RE < Growth of Demand (energy basis)

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TECHNICAL DETAIL
Supply vs. Demand: Clarifications on data

- Supply is BUSBAR, while DEMAND is at state boundaries (summation)
  - Thus, supply > demand because of ISTS losses (about 3.5%)
  - In-state transmission and then distribution losses are separate
- Demand (rather, load met – but load shedding is low) varies, with a high upto ~190 GW
  - 190 GW demand means about 200 GW of supply (generation) busbar
  - 200 GW busbar also has auxiliary consumption losses, about 8% for coal (and rising with FGD use), so needs some 220 GW supply capacity

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Supply vs Demand (Background)

- Out of gross capacity of 380 GW, about 100 GW is RE, and little of this is firm/dispatchable power
- Grid peak (absolute peak) is usually in the evening – at this peak, RE's contribution can sometimes be as low as 3-4% only (peak demand is pre-monsoon)
- Conservatively, assume firm gross supply is only ~280 GW
- For coal plants, ~15% are down at any given time with "outages" (e.g., maintenance) EXCLUDING outages because of "no fuel" or no/low demand [thus, upto 30 GW is out]
  - Similarly, Gas, hydro, and nuclear all have unavailable output.
- THUS, the margin remaining between supply and demand is only ~30 GW, maybe lower (depending on nuclear/gas/hydro outages)
- Peak demand grows ~7 GW/year, maybe more over time with rising development
  - **THUS, ~4 YEARS ABILITY TO MEET LOAD WITHOUT NEW PEAKING,** unless things change

Secondary Motivation: Difference between average energy vs. capacity

- Many studies focus on LCOE to compare fuel options ("cheapest new build")
- Our past work on coal showed some limitations
  - Fixed vs. marginal costs (new vs. already built) matter
  - Location determines cost of delivered fuel
- VRE (Variable RE) isn't good enough to meet evening demand
- A battery LCOE costs "X" ONLY if it's used in full every day
  - A more granular analysis shows that some of the battery output displaces existing fuels – not always cheaper "at the margin" when we include paying for the battery

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Model: System (2021-30) balancing and costs

- RE added is as per an exogenous plan (250-550 GW)
  - Vary wind and solar ratio (with different FUTURE shapes)
- Underutilized coal and gas is used as available
- Nuclear and Hydro increase output pro-rata as per capacity modeled (slight growth, of 3.9% and 3% CAGR, respectively)
- Demand grows as per an exogenous growth rate (not linked to price)

  [4.5% / 4.75% / 5% / 5.25%]
- A simplified despatch model stacks output to meet demand 30-min demand (post Auxiliary consumption, which varies with FGD rise, and ISTS losses – national averages for both)

Despatch ("merit order") rule:

1. Nuclear
2. RE (as growing)
3. Hydro (same shape as 2019)

Leads to (pseudo) Net Demand

1. Existing Coal as used in 2019
   - Some retirements
2. Existing gas as used in 2019
3. Under-used existing coal capacity
4. Under-used existing gas capacity
5. Residual Missing Supply = NEW something
   - Feedback to existing system from NEW source

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Model: Costs after balancing

- We treat 2019 costs as a base
- We treat existing but under-used coal/gas capacity as sunk costs
- Total costs
  - SUM:
    - Planned RE
    - Additional fuel used in existing coal/gas capacity
    - Capital Costs for NEW installs
    - Fuel costs of NEW installs
    - O&M costs of NEW installs
  - LESS
    - Reduction in energy costs of existing coal/gas (to the extent NEW suffices so far);
      - Fuel reductions via RE and/or battery for existing under-used coal/gas is already embedded above in the despatch

THUS, the output is not the total system price (since existing capacity is sunk costs)

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Study Isn't a capacity expansion *optimization*

- Treats capacity addition as exogenous choices, and compares costs that meet balancing
  - Capacity expansion cost comparisons are done parametrically
- There can be savings with optimizations, especially blending fuels for NEW supply
- The model stops at 2030 as we aren't trying to model capacity expansion per se
  - BUT amortizing costs gives a fair estimate since over time, the utilization of anything NEW will only grow over time
- We make assumptions on fuel costs over time, as well as capital costs (and USD to INR forex rate) –
  - Batteries are imported or benchmarked to global prices
- The optimal scenario will have blends of fuels, and also heterogeneity within a fuel type

The TRENDS are much more important than the specific numbers (where we have uncertainty anyways)

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There will be New Capacity required over time

- Options include: NEW Coal, OCGT, CCGT, Gas IC, Diesel, or Battery + RE
- 2 different drivers for adding capacity
  - Capacity needs for instantaneous matching
    - Should also include a buffer of 5% per Grid Code
  - Energy needs (especially where energy and capacity can shift, like with a battery)
- Battery+RE are where capacity and energy don't directly align (a 1 kW battery system charged by solar cannot give us 24 kWh output in a day)
  - Focus on modeling Daily charge/discharge cycles
- If we use a battery for all new capacity, it has to meet the higher of both needs
  - kW capacity output
  - kWh (modeled daily with daily solar inputting the battery – requires ADDITIONAL NEW (non-plan) RE to charge
  - Over time, energy needs create a capacity requirement that suffices for instantaneous capacity (MW) needs
- Existing system can suffice through ~2025 for an energy basis, but likely need a capacity buffer sooner
- *We compare most of these independently*
  - *We can add a small blend of diesel (e.g., bio-diesel) to reduce battery requirements for rare peak needs – modeled parametrically*

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Key Findings

1. The surplus of today is vital for low-cost supply
   - Avoiding a rare peak for new supply is VERY cost-effective (today ignored due to supply surplus)
   - Shifting demand to match supply will be vital – e.g., using Time of Day pricing
2. RE can grow measurably – 450 GW isn't "too much" per se
   - Curtailment (surplus RE) grows but failure to meet demand with VRE is also important
     - Flexing down thermal output (from nameplate capacity) is a bottleneck – There would be much more flex-linked curtailment than pure demand-based surplus
3. Seasonality is much worse a problem than daily swings (the latter are also more manageable via solar)
4. Firm new supply could include biodiesel (in part) to avoid expensive batteries
   - **Batteries should not be treated as LCOE-based "x" Rs./kWh**
5. Adding more wind lowers costs due to ability to meet evening supply
   - Avoids more "NEW" something, which would otherwise have a poor PLF

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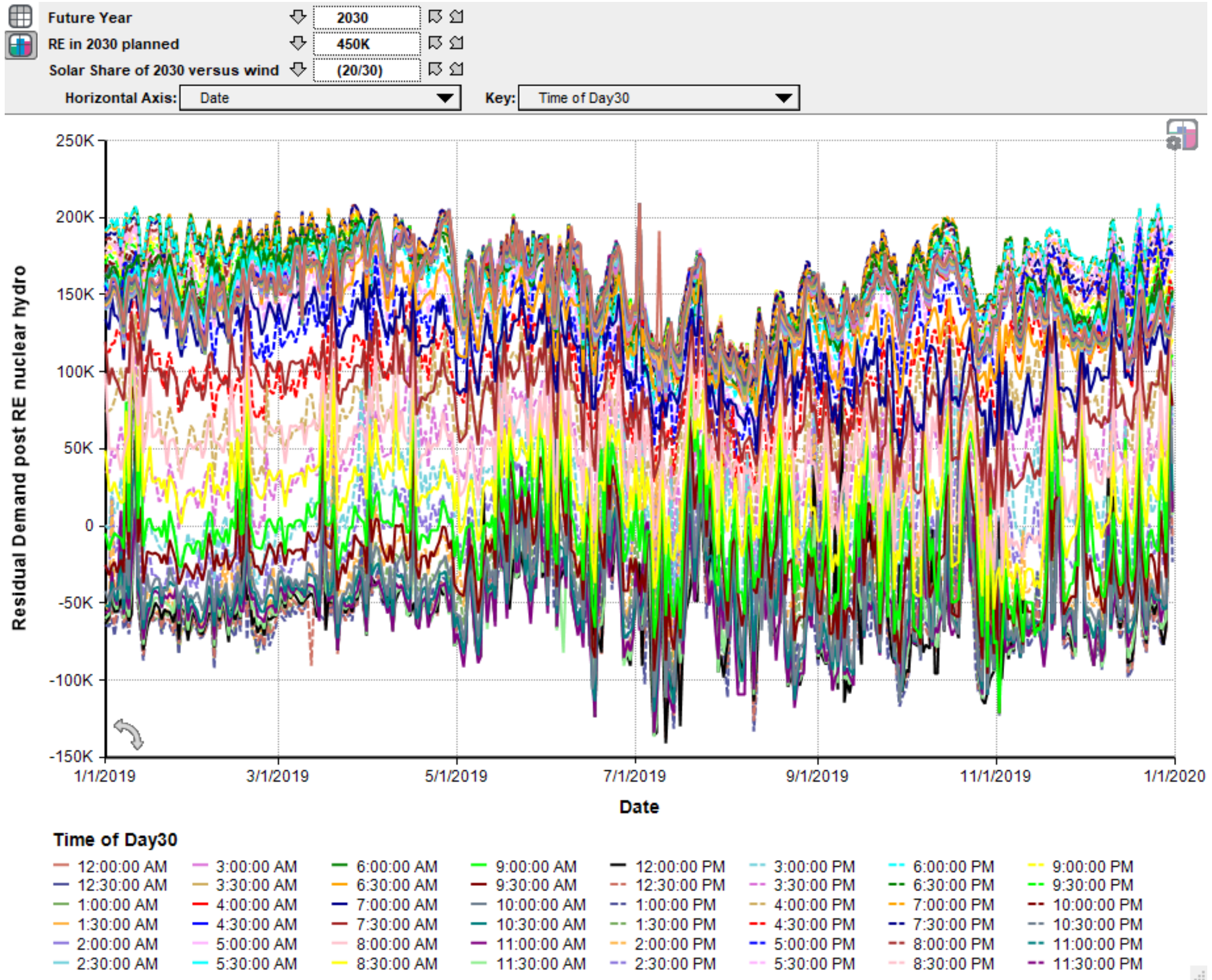
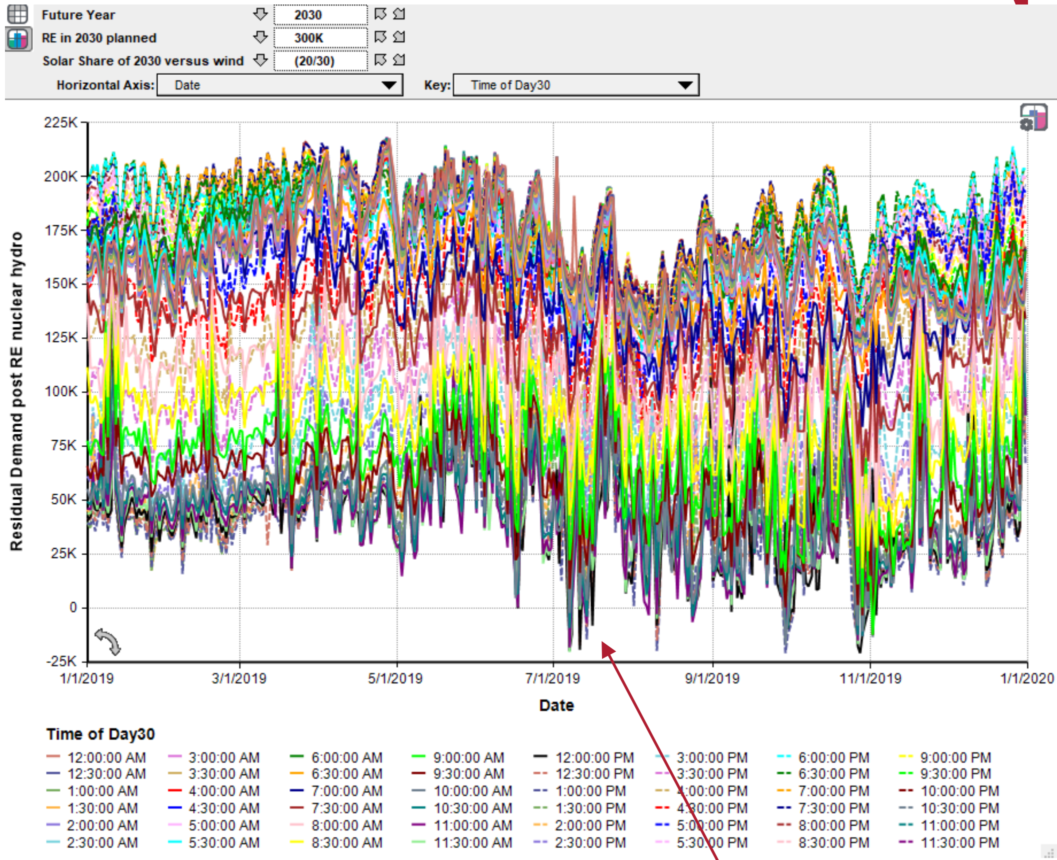
Model Base Round** – too much RE if 450 GW in 2030

** Pre-constraints on thermal flexing





mid Mid Value of Curtailment Rnd1 annual

Future Year 2030

RE in 2030 planned / Totals

Solar Share of 2030 versus wind / Totals

	15/30	17.5/30	20/30	22.5/30
250K	0%	0%	0%	0%
300K	0.01%	0.02%	0.05%	0.24%
350K	0.23%	0.37%	0.91%	2.51%
400K	1.18%	2.04%	4.26%	7.52%
450K	3.35%	5.66%	8.97%	12.85%
500K	6.8%	9.91%	13.65%	17.84%
550K	10.65%	14.04%	17.99%	22.35%

Less over-supply if RE = 300 GW

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Model 2nd Round:
Adding constraints for thermal flex down (lower output)

- Assume no daily start-stops
  - Each day's evening coal requirement using existing coal capacity gives DAILY requirements for max and thus min coal
- RE Curtailment grows heavily
- More wind helps measurably
  - We'll see the economics aren't worse either
- Flex capabilities of coal plants are also important
  - State of the art could do 40% part-load
    - New and/or retrofits required – have to consider economics
  - Fleet-wide average is assumed 60%
    - Itself will take investments – not accounted for today in "RE costs" (which also enjoys transmission cost waivers)

mid
Mid Value of Share RE curtailed
Future Year 2030
RE in 2030 planned — Totals
Solar Share of 2030 versus wind — Totals

	15/30	17.5/30	20/30	22.5/30
250K	1.59%	2.94%	5.22%	8.6%
300K	5.53%	8.96%	12.97%	17.27%
350K	11.09%	15.37%	20%	24.72%
400K	16.3%	20.9%	25.84%	30.86%
450K	20.81%	25.54%	30.61%	35.85%
500K	24.62%	29.43%	34.6%	39.99%
550K	27.91%	32.71%	37.95%	43.43%

Marginal curtailment grows non-linearly with rising RE

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Supply Mix 2021 vs. 2030 (different shares of solar:wind)

Generation (kWh)	2021
Gas	37.95G
Coal	964.3G
Hydro	159.4G
RE	153.1G
Nuclear	38.49G
NEW (something)	0
Totals	1.353T

- Coal *use* grows modestly
- Gas grows measurably (can become baseload with low RE)
  - Assuming no (net) new coal, except as replaces retirements (mild net retirement)
  - New something is for meeting unmet residual demand
- New capacity is only required by 2024 or 25
  - FIRST for meeting capacity buffer of 5% as per grid code, then for energy needs
- RE is less than half the electricity in 2030 EVEN if we hit 450 GW RE *with high CUFs*
  - Difference in RE output as usable is a combination of wind vs solar supply difference plus curtailment difference

mid

Mid Value of Annual Gen Future (kWh)

Future Year: 2030

Solar Share of 2030 versus wind: (15/30)

Flex levels thermal: 0.6

Future Fuel Mix — Totals

RE in 2030 planned — Totals

	250K	300K	350K	400K	450K	500K	550K
Gas	85.49G	69.64G	56.71G	46.11G	37.55G	30.92G	25.5G
Coal	1.114T	1.049T	999.5G	954.2G	910.3G	866.2G	822.6G
Hydro	208.9G	208.9G	208.9G	208.9G	208.9G	208.9G	208.9G
RE	552.3G	647G	719G	780.4G	836.4G	889.4G	939.9G
Nuclear	54.45G	54.45G	54.45G	54.45G	54.45G	54.45G	54.45G
NEW (something)	39.43G	25.27G	16.23G	10.68G	7.18G	4.865G	3.342G
Totals	2.055T	2.055T	2.055T	2.055T	2.055T	2.055T	2.055T

mid

Mid Value of Annual Gen Future (kWh)

Future Year: 2030

Solar Share of 2030 versus wind: (20/30)

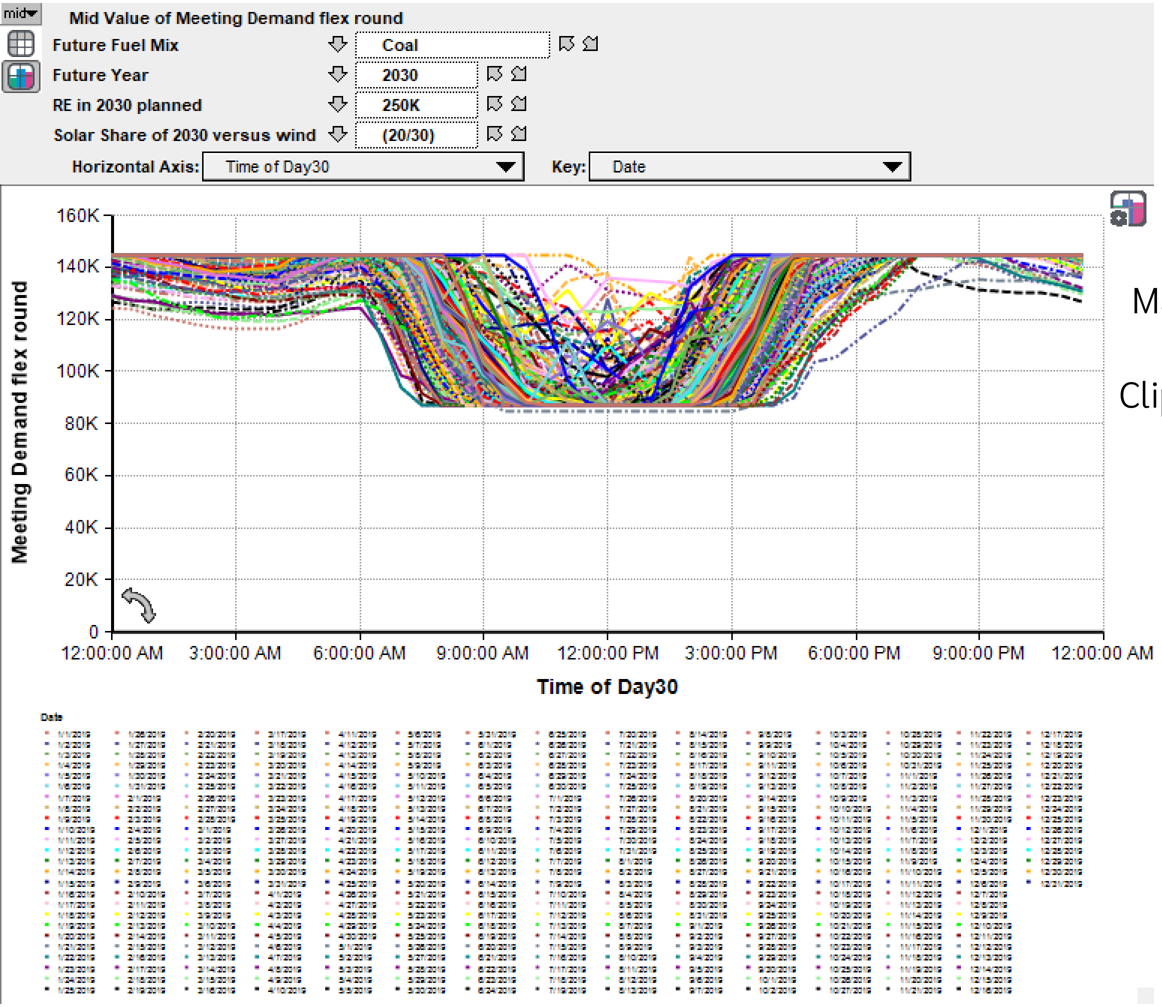
Flex levels thermal: 0.6

Future Fuel Mix — Totals

RE in 2030 planned — Totals

	250K	300K	350K	400K	450K	500K	550K
Gas	99.16G	86.9G	77.14G	68.9G	61.93G	54.82G	48.31G
Coal	1.114T	1.081T	1.055T	1.031T	1.006T	981.7G	956.8G
Hydro	208.9G	208.9G	208.9G	208.9G	208.9G	208.9G	208.9G
RE	507.2G	568.8G	617.6G	660.4G	700G	737.2G	773G
Nuclear	54.45G	54.45G	54.45G	54.45G	54.45G	54.45G	54.45G
NEW (something)	71.09G	54.31G	41.48G	31.49G	23.57G	17.66G	13.31G
Totals	2.055T	2.055T	2.055T	2.055T	2.055T	2.055T	2.055T

2030 needs lots of *existing* fleet: Existing Coal @250 vs 450 GW RE (post Auxiliary Consumption)



↔
Maxing output

Clipping the low
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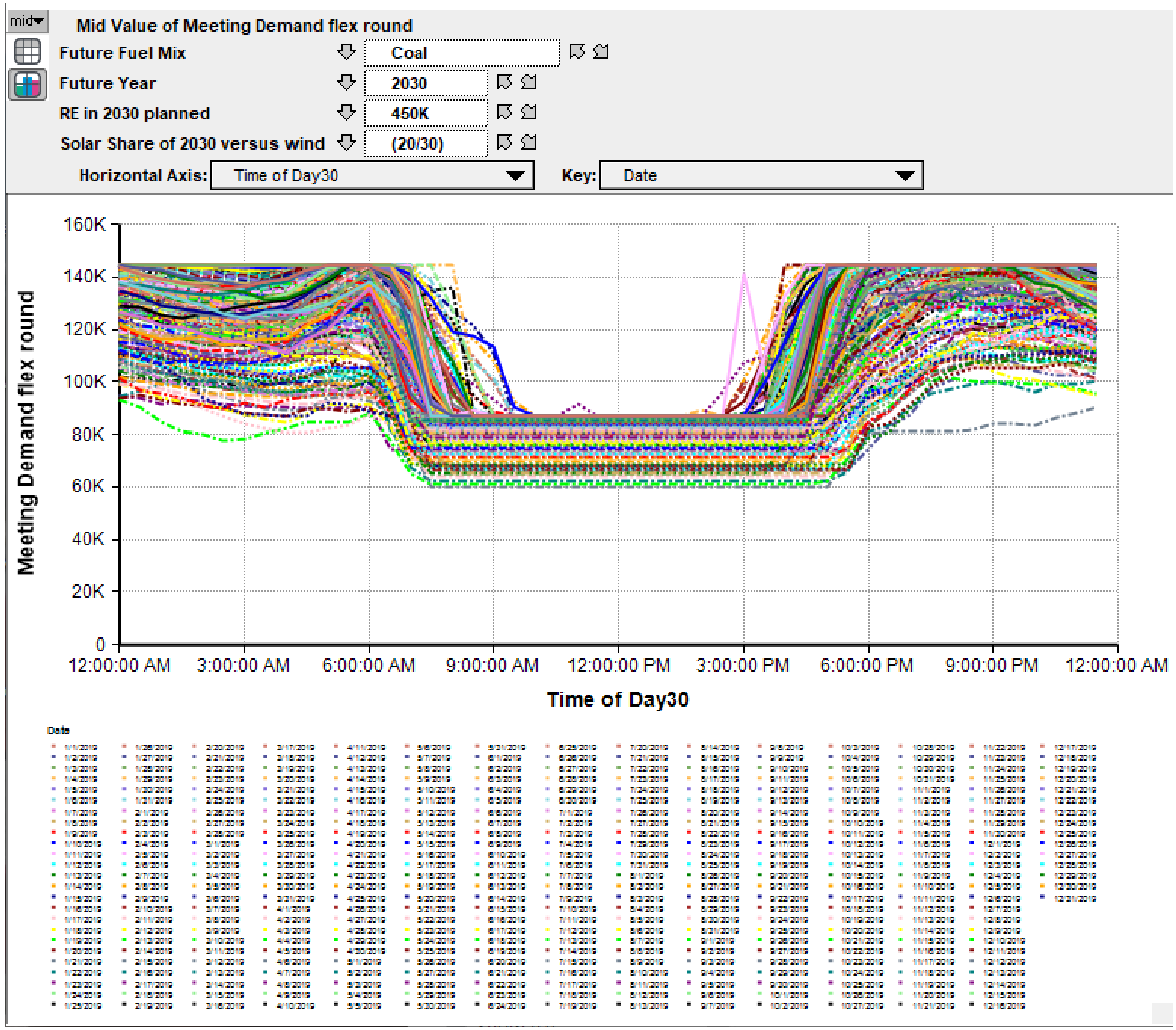

Coal still maxes out (CUF ranges from 71.7% to 79.4%) ASSUMING 2/3 solar in 2030 (as per targets); more wind = lower coal CUF
NOTE: this is w/ 2020 capacity without adding some of the under-construction capacity except to replace part of planned retirements.

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INTERIM System Economics (Rs.) – Treating existing capacity as Sunk as well as ignoring hydro and nuclear growth costs (common/sunk)

Mid Value of NPV existing system and Planned RE

- Discount Rate: 0.06
- Solar Share of 2030 versus wind: (20/30)
- WACC: 0.08
- Future Fuel Mix ☑ Totals
- RE in 2030 planned ☐ Totals

	250K	300K	350K	400K	450K	500K	550K
Gas	2.341T	2.119T	1.955T	1.825T	1.716T	1.614T	1.523T
Coal	21.34T	20.68T	20.12T	19.61T	19.14T	18.7T	18.28T
Hydro	0	0	0	0	0	0	0
RE	2.764T	3.405T	4.019T	4.609T	5.182T	5.739T	6.283T
Nuclear	0	0	0	0	0	0	0
NEW (something)				To be added			
Totals	26.44T	26.21T	26.09T	26.05T	26.04T	26.05T	26.09T

Mid Value of NPV existing system and Planned RE

- Discount Rate: 0.06
- Solar Share of 2030 versus wind: (20/30)
- WACC: 0.1
- Future Fuel Mix ☑ Totals
- RE in 2030 planned ☐ Totals

	250K	300K	350K	400K	450K	500K	550K
Gas	2.341T	2.119T	1.955T	1.825T	1.716T	1.614T	1.523T
Coal	21.34T	20.68T	20.12T	19.61T	19.14T	18.7T	18.28T
Hydro	0	0	0	0	0	0	0
RE	3.132T	3.86T	4.556T	5.226T	5.875T	6.507T	7.123T
Nuclear	0	0	0	0	0	0	0
NEW (something)				To be added			
Totals	26.81T	26.66T	26.63T	26.66T	26.73T	26.82T	26.93T

Interim results

Before adding costs of NEW supply (where there are choices)

Cost of capital matters for "lowest cost" portfolio; lower capital costs means higher RE is cheaper

NOTE: discount rate is distinct from cost of capital (WACC)

The costs (inclusive of fuel) are all relatively similar

Higher RE means less NEW required

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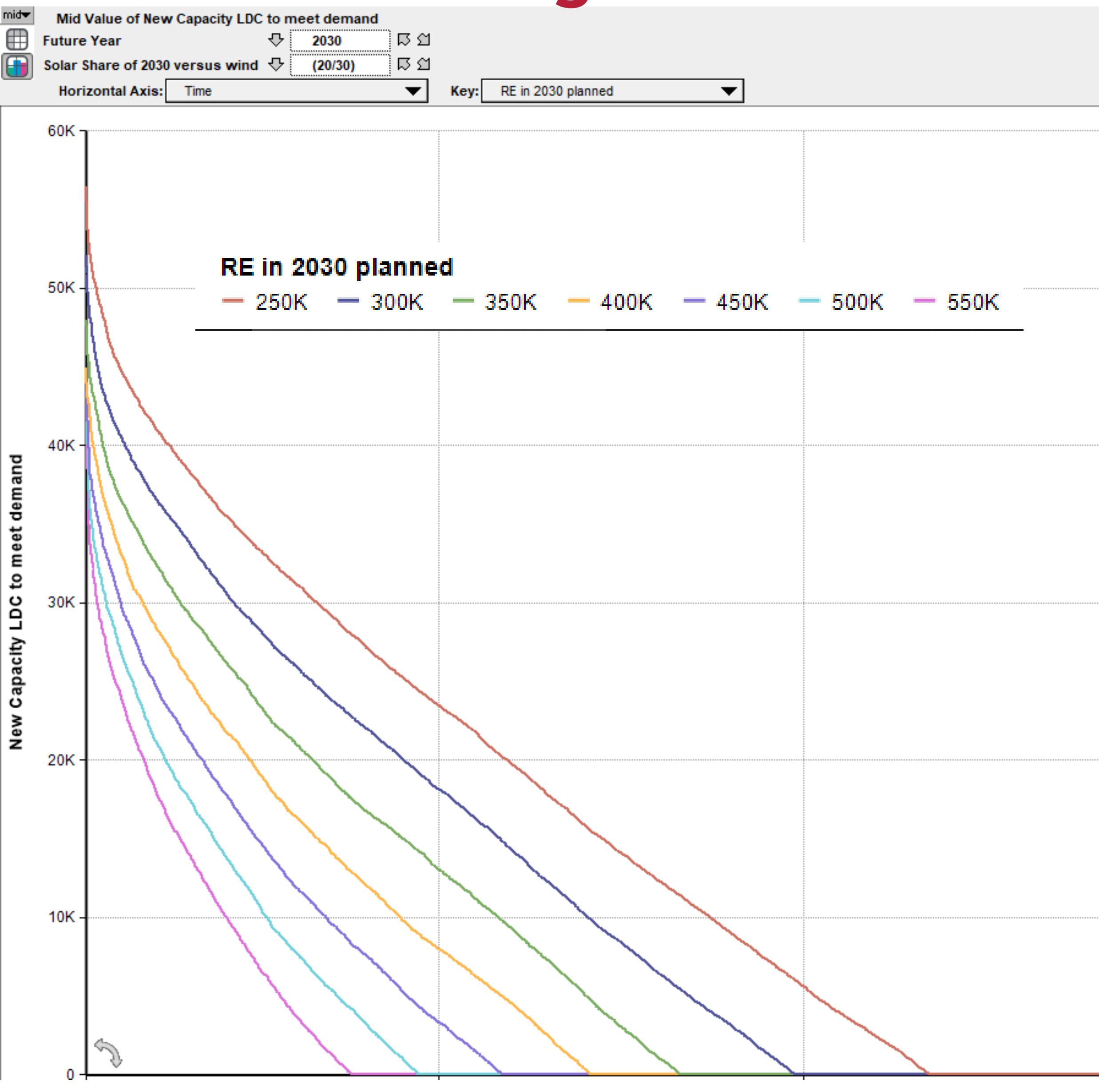
Cost of adding ANYTHING new is high due to low utilization



Stacked hour of year

Load Duration Curve = stacked curves

In 2030 need modest capacity (MW) for only a few hours per year

Mid Value of PLF New Other (energy basis only)

Solar Share of 2030 versus wind (20/30)

Future Year — Totals

RE in 2030 planned — Totals

	250K	300K	350K	400K	450K	500K	550K
2021	NAN	NAN	NAN	NAN	NAN	NAN	NAN
2022	NAN	NAN	NAN	NAN	NAN	NAN	NAN
2023	NAN	NAN	NAN	NAN	NAN	NAN	NAN
2024	NAN	NAN	NAN	NAN	NAN	NAN	NAN
2025	0.05%	0.03%	0.01%	NAN	NAN	NAN	NAN
2026	1.16%	0.81%	0.55%	0.39%	0.28%	0.21%	0.14%
2027	3.73%	2.87%	2.23%	1.75%	1.35%	1.04%	0.82%
2028	7.14%	5.73%	4.6%	3.7%	2.95%	2.38%	1.88%
2029	10.76%	8.84%	7.28%	5.84%	4.68%	3.64%	2.84%
2030	14.37%	11.9%	9.88%	7.99%	6.19%	4.63%	3.49%

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A battery can have 3 outcomes

- Some hours – used to meet new (residual unmet) demand
- Some hours – IF UNDERSIZED vs PEAK – need an alternative
- *Most* hours this can give more supply than "NEW" (unmet demand post PLANNED RE) so displaces existing fuels
    - Value equals fuel only of alternatives
        - Gas first (most expensive) but small volume to displace on a daily basis; coal next but has limits due to part-load flexing limits

Battery also needs RE to feed it – another cost since "surplus RE" rarely aligns with when battery is needed or even usable (daily cycling = limit)

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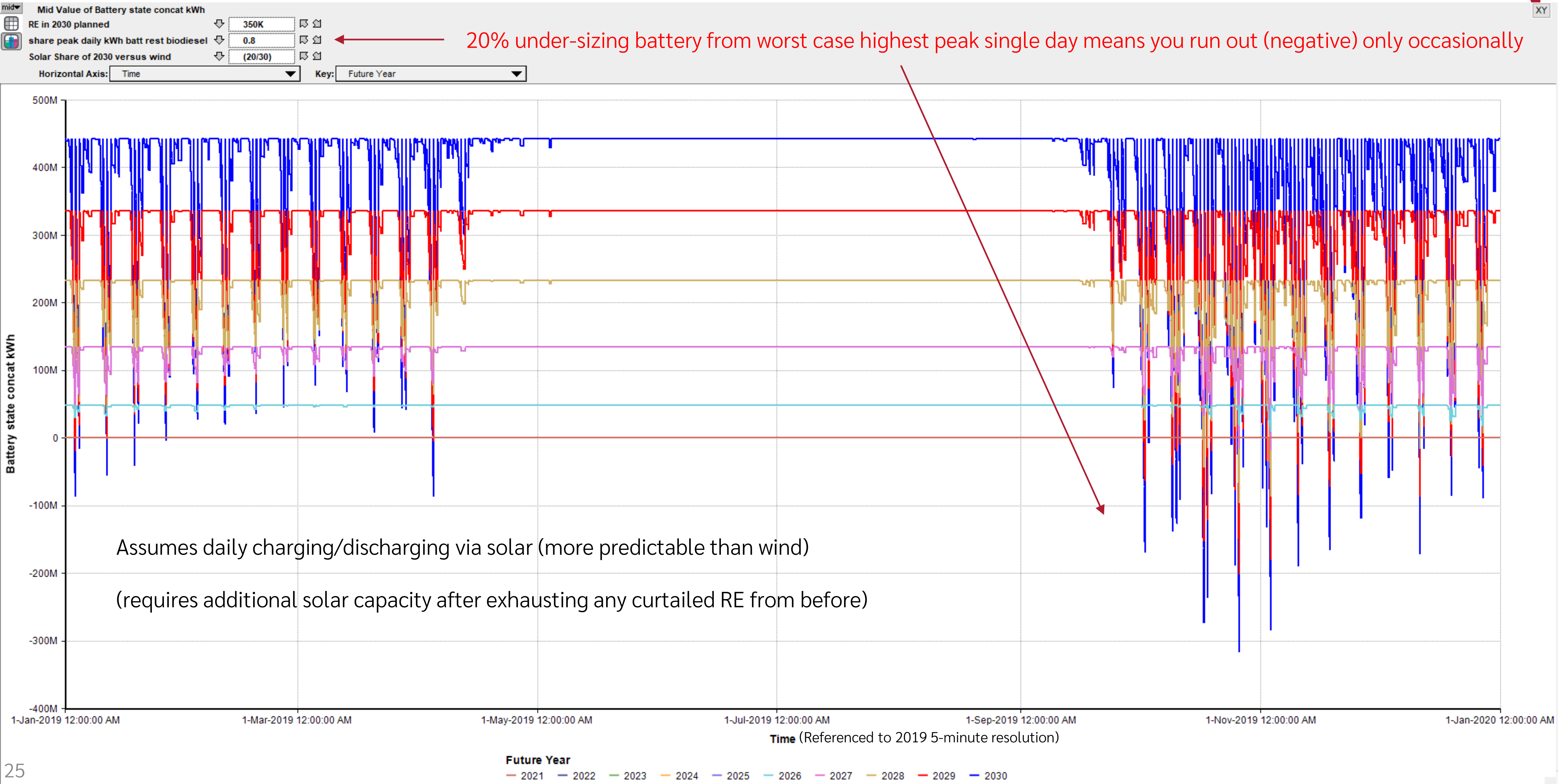
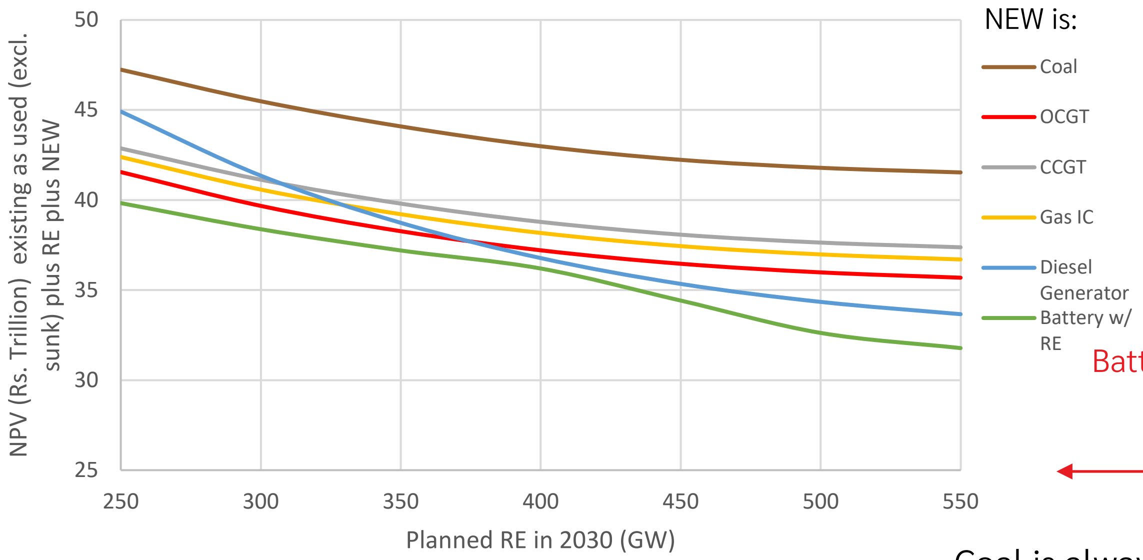
New sizing shouldn’t be 100% battery – Full use is rare



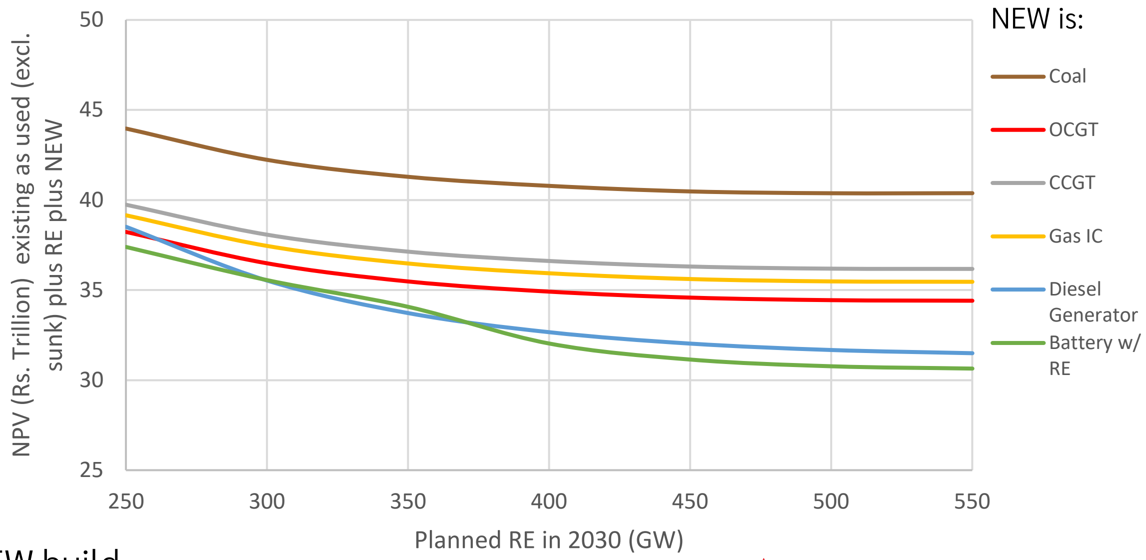
20% under-sizing battery from worst case highest peak single day means you run out (negative) only occasionally

Assumes daily charging/discharging via solar (more predictable than wind)

(requires additional solar capacity after exhausting any curtailed RE from before)



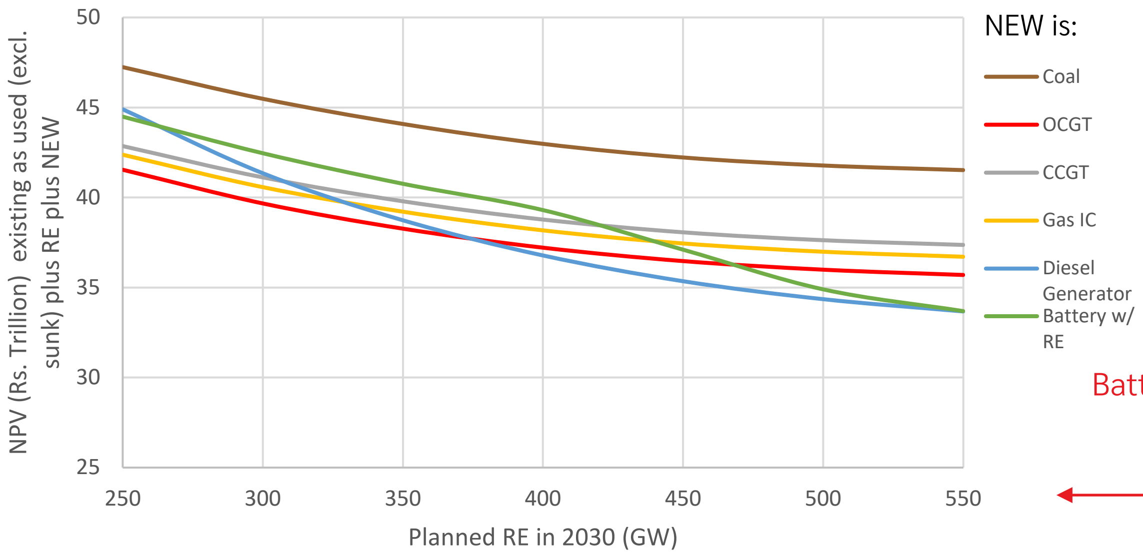
Battery sized at 20% of peak NEW; Rest biodiesel



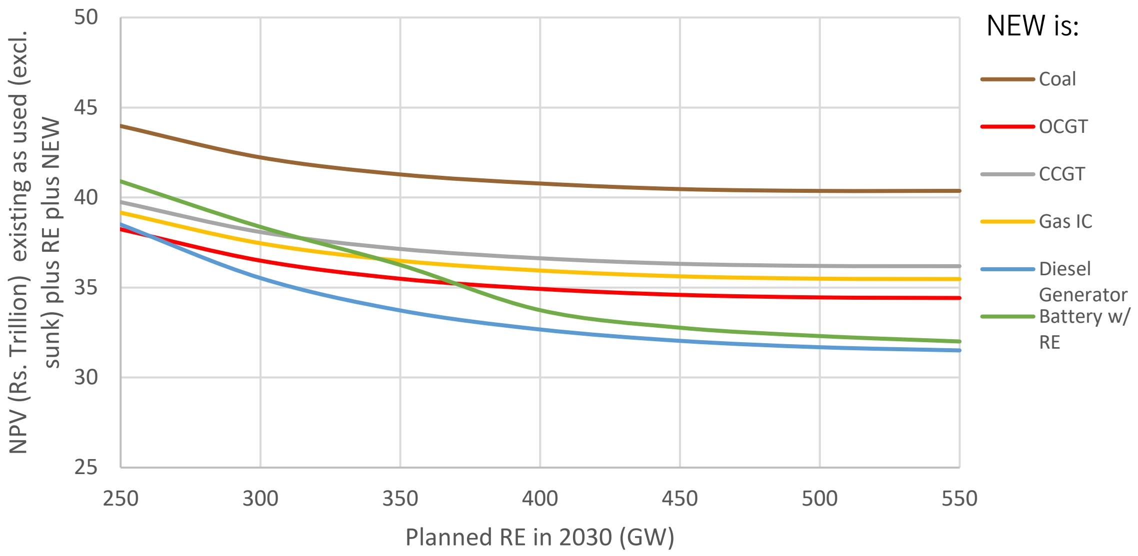
2/3 solar, 1/3 wind

Coal is always priciest for NEW build
RE + Battery *may* be optimal

1/2 solar, 1/2 wind



Battery sized at 60% of peak NEW; Rest biodiesel



NPV of Future System (Excl. existing sunk costs and Hydro/Nuclear growth) – includes planned RE

Common: 0.6% Discount Rate, 10% WACC, 3% Forex depreciation rate

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ECONOMICS of New growth

- Cheapest to add more and more planned RE (without storage)
- Cheaper to NOT use batteries 100% of NEW unmet demand but blend with something, e.g., biodiesel (low-carbon) = non-linear benefit
- New Coal plants are rarely cost-effective
  - This assumes a certain growth rate of coal fuel costs
  - BUT Coal as priced includes a lot of societal pay-in, and we are ignoring other system level costs of high RE (esp. on transmission)
- What to use for residual depends on how much RE is built, and share solar:wind
  - And these VRE sources have can vary YoY, especially wind
- Avoiding new peak demand may be the cheapest (smart grids, demand response)

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BioDiesel can help fill unmet demand with zero-C

- Diesel generator has low capital costs, high operating costs (perhaps Rs. 18-20/kWh)
  - But still affordable because volume is low
- Land requirements
  - 10 billion kWh needs 27,360 sq. km for jatropha based biodiesel, or 233 cr. L
    - 850 L per ha, 4.3 kWh/L
  - Reducing battery requirements by 40% saves significant capital and adds much less in fuel costs
- Benchmarking: 20% ethanol blend implies ~upto 1016 crore L ethanol

mid

Mid Value of Unmet demand via battery (kWh)

Solar Share of 2030 versus wind: (20/30)

share peak daily kWh batt rest biodiesel: 0.6

RE in 2030 planned — Totals

Future Year — Totals

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
250K	0	0	0	0	0	54.37M	849.3M	3.992G	10.26G	19.37G
300K	0	0	0	0	0	23.64M	347M	2.32G	6.757G	13.76G
350K	0	0	0	0	0	11.92M	197M	1.283G	4.339G	9.358G
400K	0	0	0	0	0	5.268M	131.7M	811.4M	2.777G	6.149G
450K	0	0	0	0	0	3.35M	96.74M	588.8M	1.954G	4.239G
500K	0	0	0	0	0	2.67M	70.74M	442.9M	1.487G	3.125G
550K	0	0	0	0	0	2.367M	52.75M	370.8M	1.156G	2.455G

Non-linearities from not sizing battery for the worst-case peak in the year mean only modest unmet demand to be filled (e.g., via biodiesel)

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Carbon avoidance cost depends on how much you want to displace

- Avoiding carbon from coal is primarily about avoiding new capex of coal – but hard to displace much of existing coal, more so beyond using VRE
  - Good new is there is still some scope for usable VRE to be cheaper than marginal cost of coal, but that will disappear well before RE targets are met

- It's not just carbon externalities – coal pollution has a cost
  - But the flip side is coal today also pays into taxes/levies/cess and for the railways

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Policy Insights

- Need to stop adding more capacity (based on LCOE) and instead look at *system level costs*
  - Including transmission
- Existing capacity needs to maintained
  - Carbon worries? Less a problem for the coming decade
    - Step 1: Avoid NEW carbon capacity instead of retiring existing
- ToD really matters, including net demand
- RE wind:solar ratio matters – but wind shapes change much more with location (and YoY variations)
  - Wind has a higher LCOE but greater system value over time – lower marginal curtailment as its share rises AND greater ability to meet upcoming peaks
- There is LOTS of uncertainty going forward
  - Need stochastic modelling as well (demand, weather, etc.)

Shapes (supply AND demand) Really Matter

- Demand Side – need many instruments to align
  - 4.75% growth pro-rata is still under 300 GW peak load met
    - India hit 200 GW load met in July 2021
  - Need time of Day signaling to align demand with supply (instead of the other way around only)
    - We are moving towards more integrated dispatch and power markets
      - Are we ready for negative pricing mid-day?
      - As RE rises, it marginal value declines (and marginal cost of integration rises)
        - California found 19% RE lowered wholesale prices by 27+%
- RE – how will it grow?
  - Manufacturers don’t like exponential (Tongia, 2016) – they prefer steady (linear) commissioning

Socialization of some costs may be optimal

- Much of New Capacity rarely used – it benefits everyone
  - But it's pricey – can't charge on kWh basis (and TO WHOM?)
- Even start-stops of coal plants are expensive – how will this be compensated?
  - If "economics" says only certain plants should do this, will they be paid more?
- Need to pay for resiliency and uncertainty
- Backing down RE?
  - Which plant is to be curtailed? Highest marginal cost? All are zero!

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Do you need new coal?

- Model assumes only modest retirement; some growth of under construction gives model input as “net retirement”
  - Subsequent new coal is treated as “something new”
  - Can create a module for new PLANNED coal from under construction
    - *Need to know the incremental cost to finish these plants*
    - Model embeds new coal vs. retirements to get net coal capacity over time
- Gas becomes available as a filler
- There remains 10s of GW of “something else” needed by 2030
  - Should it be coal? Unlikely – because by the time you justify high new coal PLF, battery economics will further improve

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Uncertainty is enormous, e.g., how much coal do we need in 2030?

{Present coal generation is under a bit under 1,000 BU}

Compare 2 possible ranges for 2030 (with 5% demand growth)

- 450 GW RE (the target)
- Equal wind and solar (like today)
- Coal plants able to flex down to 55%

Generation from Coal (only utilities) :
915 BU = PEAK COAL IS FEASIBLE

- 350 GW RE
- 2:1 solar:wind (as per targets)
- Coal flex only 60% on average

Generation from Coal (only utilities) :
1,070 BU = Don’t hit PEAK COAL

This is before using a battery, which can displace coal from periods it is not needed for NEW DEMAND GROWTH – we don’t know the chosen “new” – can be some under-construction coal plants?

There are many other uncertainties, esp. on coal plant retirements and capabilities

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How much coal slack is there?

{slack is defined as built capacity that is under-utilised}

- While there remains some gas slack as well, gas is both more expensive and has more fuel supply issues at a plant level
- Coal plant busbar supply in India in 2021 crossed 144 GW several times
  - This translates to 156.5 GW of gross generation, assuming 8% aux. consumption
- Some fraction of the fleet will always be down for maintenance and technical limits (even assuming perfect fuel supply)
  - Thus, the slack from coal might be only 20-25 GW at most
    - FGDs if implemented also lower output
  - Optimal gas/hydro swings buys a bit more slack, but it cannot handle all the evening peak growth projected for 2030 for net demand (perhaps crossing 240 GW)

RE reality check and implications

- Because of the disconnect between kW and kWh, one cannot use LCOE to price a battery
  - Literature with "solar plus 25% storage blend" is WRONG as we may have to size it for 50% but, e.g., only use it half the time (=25% on average only on an *energy* basis)
- Today about 65% of present demand falls outside RE's present output
- India's 2022 ambitions were for 175 GW – they're close to 100 GW today
  - Even without covid was this simply BHAG?
- What does an even higher target mean?
  - More gap – what happens to the system if we fail to meet plans?
  - Crowding out of alternatives
- Less RE means more of "something else" and also value for keeping existing coal/gas alive (excluding limited planned coal retirements)

Grid RE to green hydrogen is also not cost-effective through 2030 at the minimum

- We don’t have too much “surplus” RE
  - We’re behind on RE plans as it is
- Curtailment doesn’t offer much “free” energy (which is less than straight RE, which only has 27-36% CUF in the future)
- Low CUF of RE further hurts green Hydrogen

Things we don’t know well

- Prices!
- Stochasticity – hurts the picture (need more capacity for low wind/rain/etc. or high heat aka high demand)
- State level, plant level, and unit level issues?
  - Can only make the picture WORSE than national, which assumes perfect despatch/transmission
- Demand shifts (shape curves)
- What is the impact of rooftop solar?
  - Shifts demand growth expectations (and lower CUF)
- RE curtailment for other reasons than national balancing (local, contractual, etc.)?
- If we fall short of the target/plan (e.g., 450), how so? Pro-rata wind and solar?
- What happens post 2030? Much more uncertainty, and more retirements of existing capacity
  - But we can revisit 2024 and 2027 – enough time to figure things out

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