Behind Cheap Storage Bids Is an Expensive Leftover

Residual Demand and Portfolio Costs of Firm(er) Power in India

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Disclaimer: Preliminary Results – Peer Review in progress

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Study: What do current cheap storage bids mean?

- India's newest storage+solar bids are remarkably cheap, some even cheaper than new coal
- But details on what the bids actually promise matter

  Most cover limited (the easy) hours, with generous relaxations for the hard ones
- The hard hours do not disappear

  They become "leftover" (residual) demand that the grid / discom / consumers still pay to serve
- We study what the headlines skip, viz.:

  (1) The cost of genuinely firm (hourly) 24×7 clean power, and (2) the cost of the leftover when bids avoid it
- **Bottom line:** India needs much more storage…but the true cost of reliability must be visible, or it quietly lands on DISCOMs and consumers

Six terms that carry this analysis

1) **LCOE:** Levelised Cost Of Energy (or Electricity); the all-in cost per unit (₹/kWh) over a *project's* lifetime
2) **CUF:** Capacity Utilisation Factor (akin to Plant Load Factor, or PLF): total energy delivered over the year as a share of the maximum
   (It counts energy, not which hours)
3) **Firmness:** the share of demand the storage project must meet in every hour (time block), not just on average
   (95% firm = match *minimum* 95% of demand in every single hour)
4) **Relax worst hours (Cost-optimized):** Allow small % of hours (e.g., 5%) for relaxation in firmness
   (bids would allow upto 5% relaxation per hour; a 5% reduction in annual CUF is easier – can be any hour(s))
5) **Residual ("leftover") demand:** the hours a project does not serve; the discom must procure elsewhere
6) **DISCOM:** the distribution company that buys power for consumers; it absorbs the costs bids leave out

Other key terms: RTC = "round-the-clock" (tenders); FDRE = "firm and dispatchable RE";
VGF = viability gap funding (an upfront subsidy)

Clean Energy – How we got here:
From "sell what you generate" to "24×7 cheaper than coal"

- **Phase 1 – "vanilla" solar and wind:** generate when you can, sell what you produce.
  (No duty to match demand, no storage; surpluses simply curtailed)
- **Phase 2 – RTC and FDRE tenders**: bundled solar, wind and storage and asked for reliability
  But time-of-day mismatches were built into the designs, and the hourly firmness required was lower (annual/monthly averaging, relaxations, etc.)
- **Phase 3 – today's storage + solar (SECI, NHPC, SJVN)**: ₹3.09 to ₹6.45/kWh but not easily comparable
  Vary by coverage, e.g., for only 2 or 4 peak hours a day, some with solar blending, with ±10% to 15% annual tolerance and no strict hourly matching
  Stacking such bids does meet true 24x7 demand; the worst hours still need oversizing)
- Standalone battery rentals have fallen 86% in three years, from ₹10.83 lakh to ₹1.48 lakh/MW/month
  But these leave the buyer (discom/utility) to deal with charging the battery
- New claim: storage + solar can now deliver 24×7 power cheaper than coal
  (several analysts say the firm-power problem is solved)
- Our question: Cheap, yes...but what exactly is promised, and who serves the hours left out?
  That cost moves to the grid, the DISCOM, and low-utilisation coal/peakers

Three layers of Cost

Reliability, robustness, and integration significantly increase RE *system costs*

1. Tender 'RE + Storage' Cost (what is usually quoted)

- Often based on energy delivered (e.g., ₹/kWh) *assuming a certain output and duty cycle*
- Most bids have limited or "relaxed" supply obligation
- Annual, monthly, and even peak-hour obligations exist, yet the penalty is calculated on a *monthly average basis*

Grid/utility absorbs the cost of this variability and balancing (unserved demand)

2. Firm(er) RE Cost (revealed when firmness is imposed)

- Low firmness: avoids difficult hours → lower RE/ storage size and cost
- High firmness: covers tougher hours → much higher RE oversizing, storage, and cost
- Robustness cost: handling tough years and extreme conditions requires extra capacity, storage, and reserves, increasing overall system cost

Same CUF, different firmness costs

3. Full RE System Cost (system-level portfolio)

- **Level 1: Unmet demand.** If RE + storage covers less than 100% demand (e.g., 85%), the remaining supply needs costly low-utilization sources like coal, gas, or peaking plants (costs must be examined on a portfolio basis)
- **Level 2: Beyond the project.** Even with 100% RE + storage supply, extra costs remain for transmission, reserves, grid stability, and backing down other generators beyond RE/battery costs *(outside the scope of this study)*

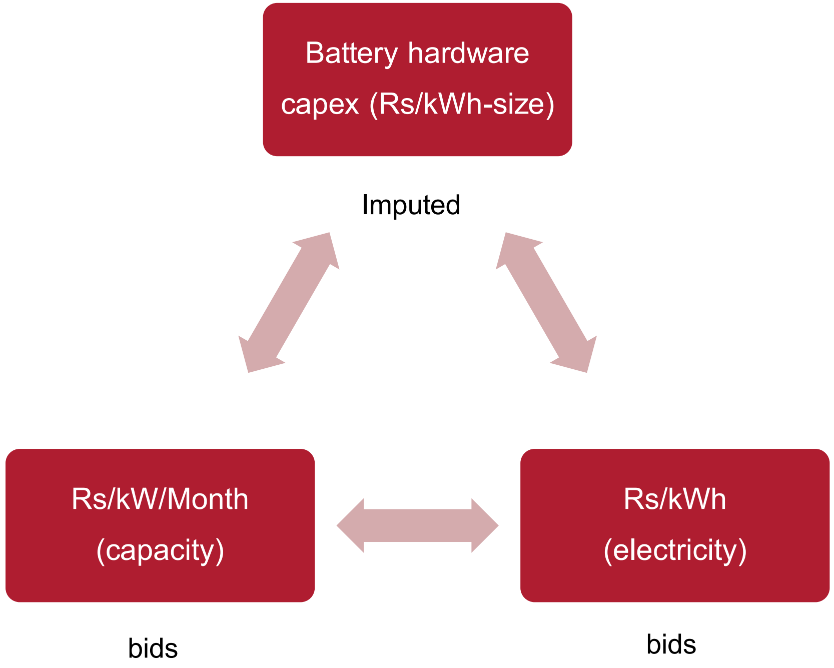
Portfolio costs go beyond rising firmness costs, and full system costs are even higher

Part 1 – What do the cheap bids actually promise?

Reading the fine print behind the headline ₹/kWh

Storage bids are not directly comparable

The same hardware can yield very different ₹/kWh, depending on assumptions

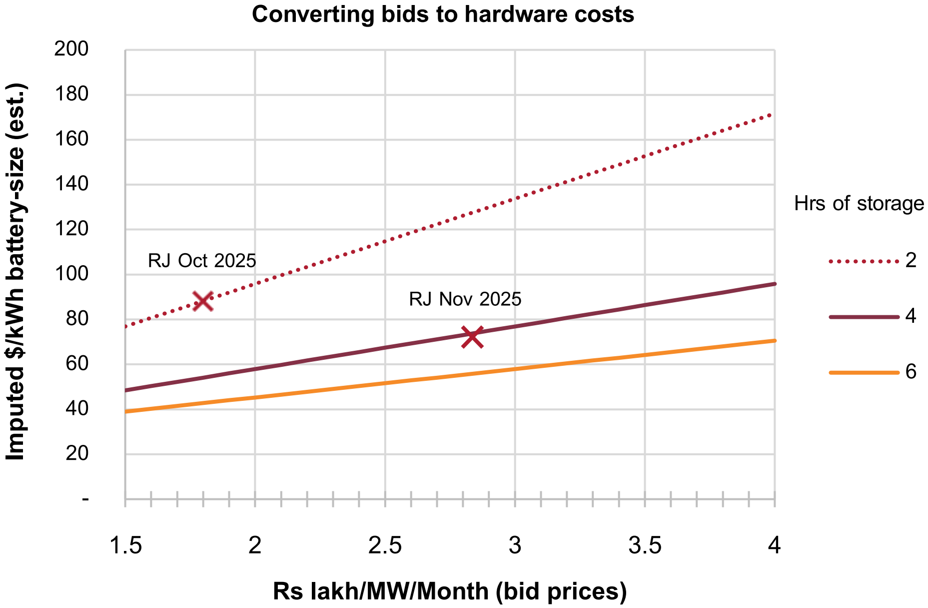


Arithmetically convertible into each other, but only if you make assumptions like duty cycle

- Bids can come in different units: ₹/kWh of battery hardware, ₹lakh/MW/month rentals, ₹/kWh of electricity delivered, etc.
  Converting between them requires assumptions
- The biggest assumption is the duty cycle: Assume two full daily charge-discharge cycles and the per-unit electricity cost looks far cheaper
  But how, and at what price, will it charge twice a day?
- Many bids also include VGF (an upfront subsidy) that the headline tariff does not show
- Hardware is more than cells/packs: inverter, electronics, cooling, installation
  Press focuses on packs, which are largely imported

Many bids have entered the realm of "challenging"

Risks: (a) quality (esp. for Indian heat); (b) will it get built?



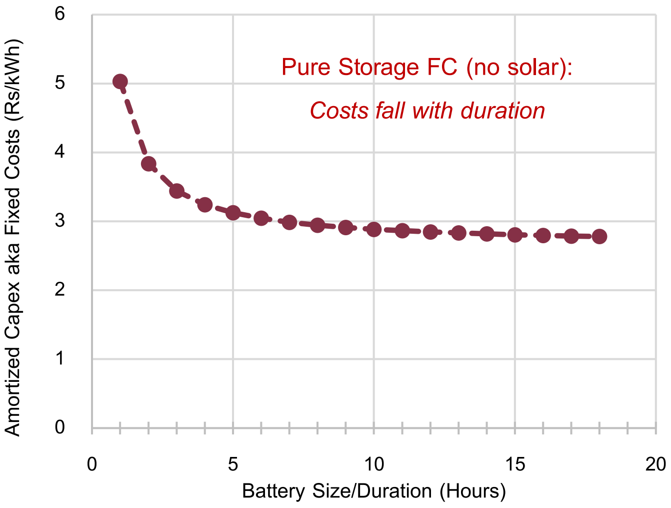
- $~74/kWh-battery *system costs* is quite aggressive considering:
  - Installation
  - Duties
  - Balance of systems, including inverter!
- The cells (if imported) thus are in the order of ~$42/kWh!

By Dec 2025, China tightened export rules: no selling batteries below cost (EBITDA-negative)

Blended (w/ solar) bids complicate comparisons

Simplistic modelling (linear arithmetic)

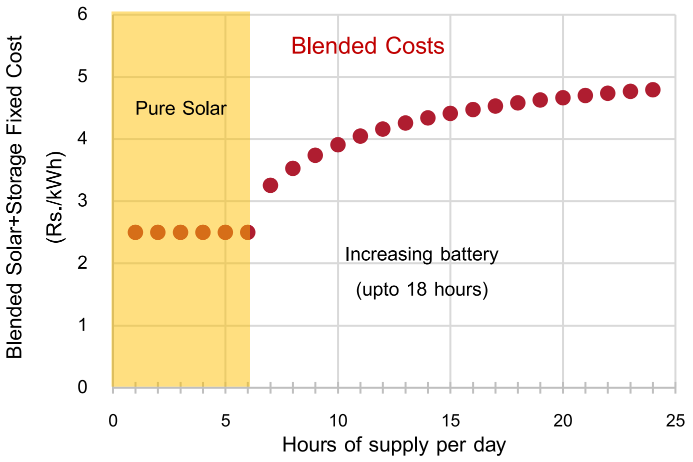
- FDRE (firm & dispatchable) bids asked for (say) 4 hours of overnight supply



Pure battery: Larger size is cheaper as BoS costs are based on kW, not kWh

Solar farms can give 25% PLF = 6 hours per day

Thus, 18 hours of battery + 6 solar = 24 hours supply (*on paper*)



Solar + Storage: Costs rise with more hours/day of supply (solar is cheap)

Notes: Storage assumes a pack cost of $50/kWh, BOS (balance of system) cost of $50/kW, EPC/installation of $10/kWh, 10.15% WACC, 12 year lifespan, 3% O&M costs, Round trip efficiency of 85%, 90% depth-of-discharge (DoD) limit, Rs 90/US$ forex rate, and one cycle per day in full

A recent bid: UPPCL storage (May 2026)

Storage with RE for charging included, but not blended with direct solar

- The bid pays for just 4 hours of discharge, during evening/night periods
- Headline tariff: ₹6.45/kWh, plus viability gap funding worth roughly another 70 paise/kWh
- Blend in cheap solar for 6 hours equivalent (₹2.50/kWh, an aggressive assumption) and a simple weighted average for “24×7” converts to about ₹6.0/kWh
- But see the fine print:

  (1) The bid requires only 95% availability, measured monthly, not hour by hour; (2) that is only for a flat output
- **Takeaway**: even at ₹6/kWh for 24×7, this is not yet truly firm power

Part 2 – What does genuine 24×7 clean power cost?

We build a model that starts simple and adds reality one constraint at a time
(The goal is not a single price, it is to see which assumptions move the price)

Pro Tip: Don’t focus on a specific cost result, but the *changes in cost* or trends when we add constraints or factors that matter

Wonky details:
Built in GAMS · Thousands of MIP (Mixed Integer Programming) problems to solves a single MINLP Problem · Thousands of runs for Demand Flexibility in loop · Planning with Operational Granularity
Needs powerful computing (days per run): Intel Core i9-14900K 3.20 GHz, 192 GB RAM System

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The biggest problem with headline 24×7 claims is extrapolating from current bids (often linearly)

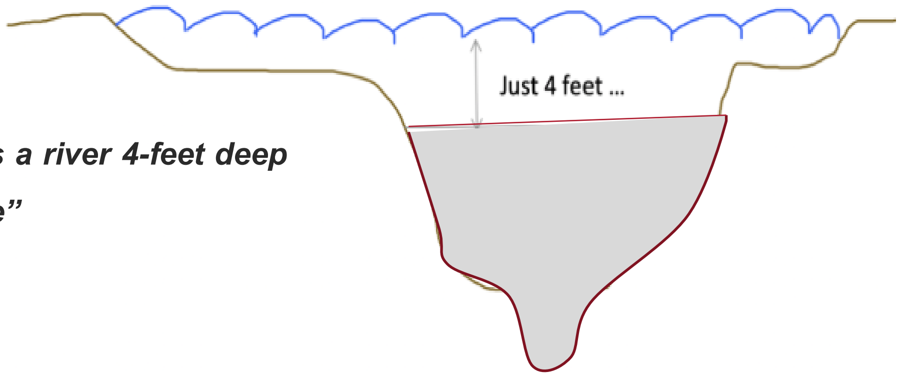
- The goal isn't the produce a flat demand like current bids (even ignoring lack of firmness)

  Demand varies by season, as does RE supply

- Lack of firmness isn't a cost reduction, it's a risk transference

Never cross a river 4-feet deep

"on average"



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Every real-world constraint you add moves the cost

Simplified System Assumption
Flat demand, identical solar, no constraints

Round-trip efficiency (RtE)
Energy loss during charging/discharging

Depth of Discharge (DoD)
Maximum battery discharge limit

O&M
Operations and maintenance costs

Degradation
Battery capacity decline over time

Solar is not Identical Each Day
Variable solar generation

Demand is not flat

C-rate limits restrict charging and discharging

Time-block mismatches between supply and demand

National Solar Profile has different shape as well as CUF

Year on Year Variability in Demand and Solar

Spreadsheet calculations can estimate this with reasonable accuracy

These require optimization with ToD matching

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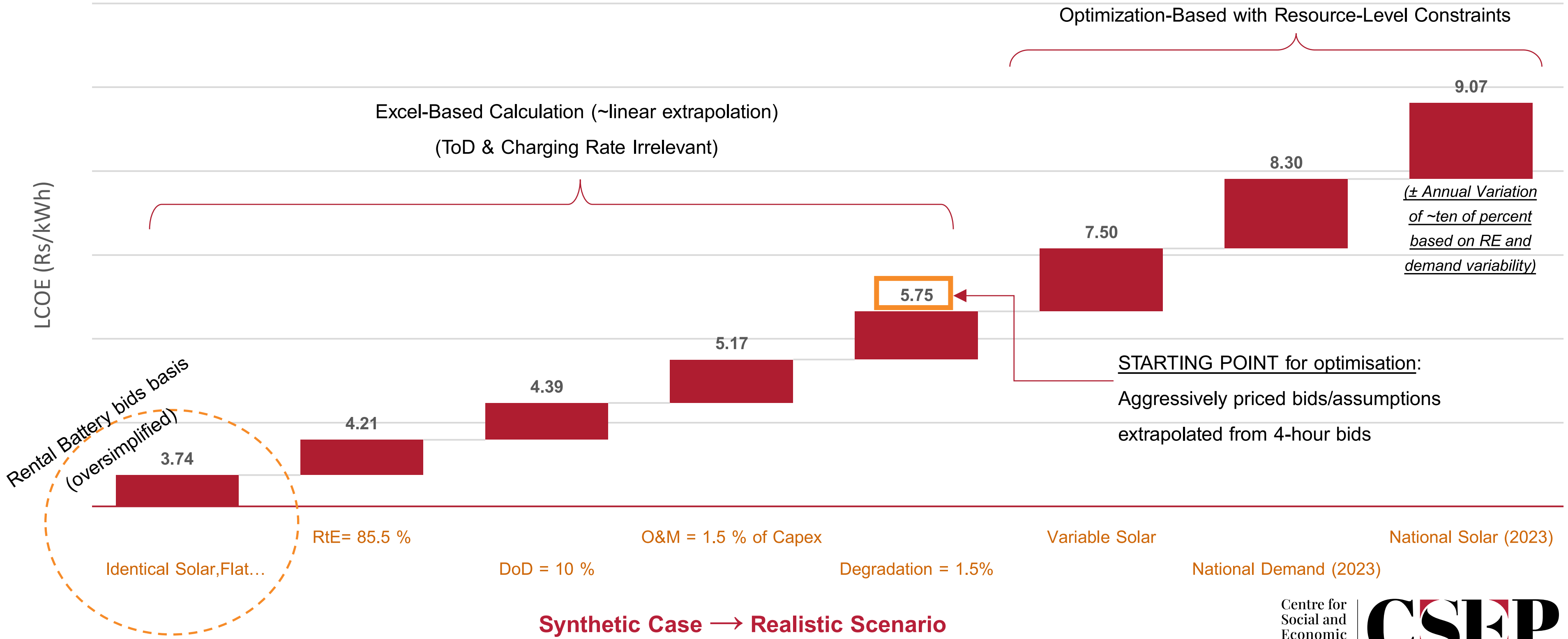
The cost of "24×7" power: same technology, very different price

Small changes in modelling constraints and assumptions can significantly change costs

(Adding constraints layer by layer: Cheapest is flat demand, identical daily good solar output)



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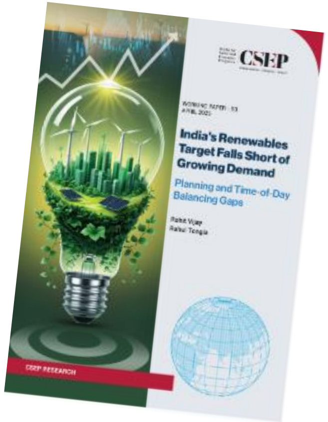
Why do costs rise with real-world profiles?

Both demand and supply aren't identical in shape over the year (aka seasonality)

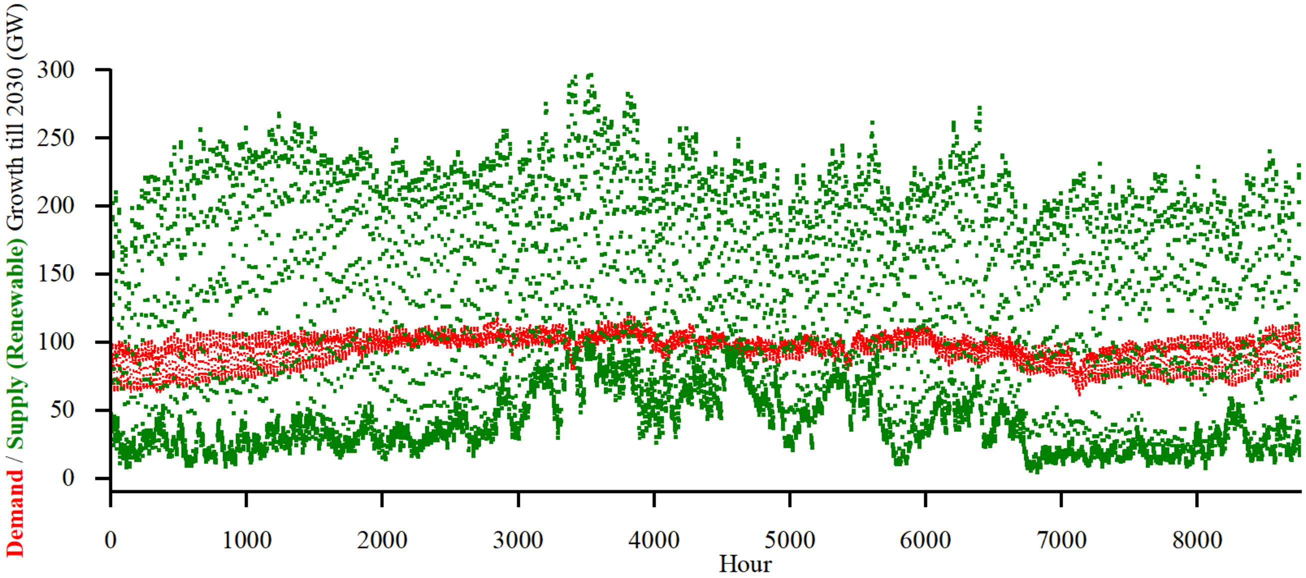
- Solar dominates India's RE supply, and it varies not just day-to-night but season-to-season
- Demand varies by season even more, and the two do not move together
- The mismatch is largest in exactly the periods storage finds hardest: long cloudy, hot (high-demand) stretches
- Our 2025 study documented this planning and time-of-day gap in detail:
  - Vijay and Tongia (2025), "India's Renewables Target Falls Short of Growing Demand: Planning and Time-of-Day Balancing Gaps"

    https://csep.org/working-paper/indias-renewables-target-falls-short-of-growing-demand-planning-and-time-of-day-balancing-gaps/



2025 Study Highlights (1): “Enough” on an annual average basis has Time of Day (ToD) mismatches

Incremental per time block demand vs. energy adequate wind + solar supply



Areas of surplus and deficit are equal

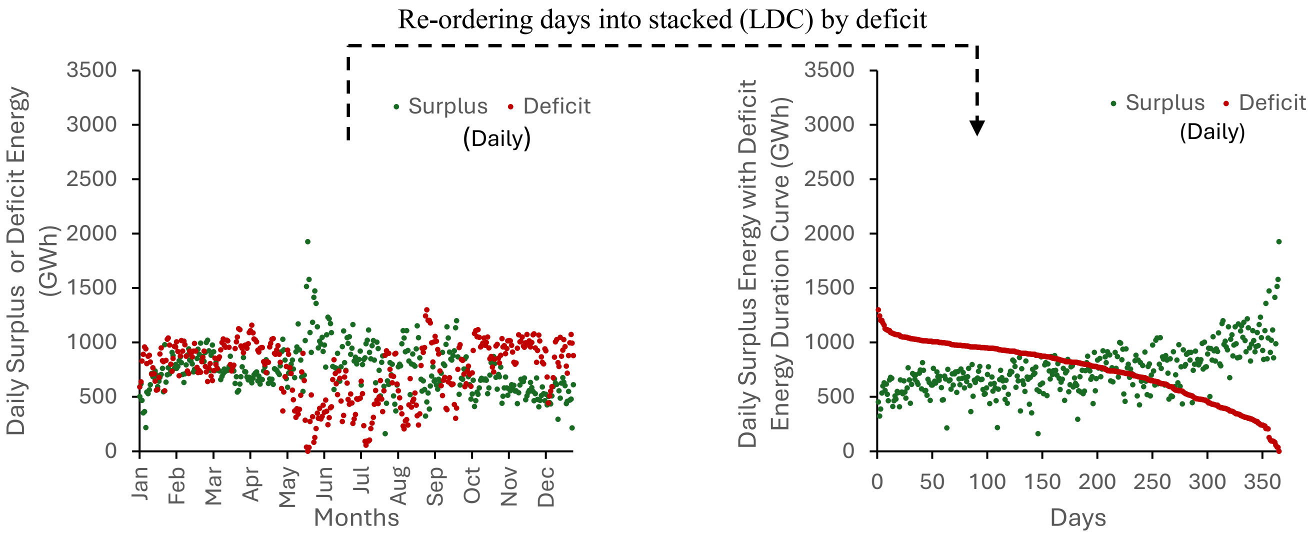
…so at first glance, this suggests that surplus energy can be stored and later used to cover deficits (even adding for round-trip-efficiency losses

Demand Growth: Pro Rata, Solar:Wind Ratio of 2; 2023 Annual Average CUF

Hourly data across the year (8,760 hours), where red points represent incremental demand and green points represent new VRE output

Source: https://csep.org/working-paper/indias-renewables-target-falls-short-of-growing-demand-planning-and-time-of-day-balancing-gaps/

2025 Study Highlights (2) – Storage has a seasonality problem: Daily Surplus and Deficit and Load Duration Curve (LDC) of the Deficit



Surplus-Deficit Misalignment & Storage Challenges

- India's grid is solar heavy, so daily balancing of RE to charge required storage is key
- Surplus and deficit days rarely align — high deficits coincide with low surplus, and vice versa.
- **To meet the worst case days, need a larger battery (will be underutilised other days) AND extra RE to charge (our study does that optimisation)**

Load Duration Curve (LDC): Daily deficit is plotted in descending order, and the same day's surplus is plotted simultaneously.

Assumptions:

(Pro Rata Demand, National 2023 RE CUF, Solar Heavy Mix)

Source: https://csep.org/working-paper/indias-renewables-target-falls-short-of-growing-demand-planning-and-time-of-day-balancing-gaps/

Part 3 – The workaround: promise less than everything

Relaxing the obligation makes bids cheaper…but the hours you skip are precisely the expensive ones

“Firmness” isn’t the same as energy served

- **CUF is a promise about the year as a whole:** Total energy delivered over the year, regardless of which hours it came in
- **Firmness is a promise about every hour**: At 50% firmness, the project must supply at least 50% of demand in every time block of the year; at 100% firmness, it must match demand in every single hour
- **Firmness dominates CUF:** Even a low firmness promise still delivers a lot of annual energy, because system output often exceeds the minimum

Thus, a bid can showcase a high annual CUF while quietly skipping the hardest-to-serve hours

High CUF $\neq$ reliable supply

Two Ways to Achieve the Same Energy (CUF) — Very Different Costs

Meeting every hour is expensive; relaxing a few worst hours sharply reduces cost without necessarily changing annual energy

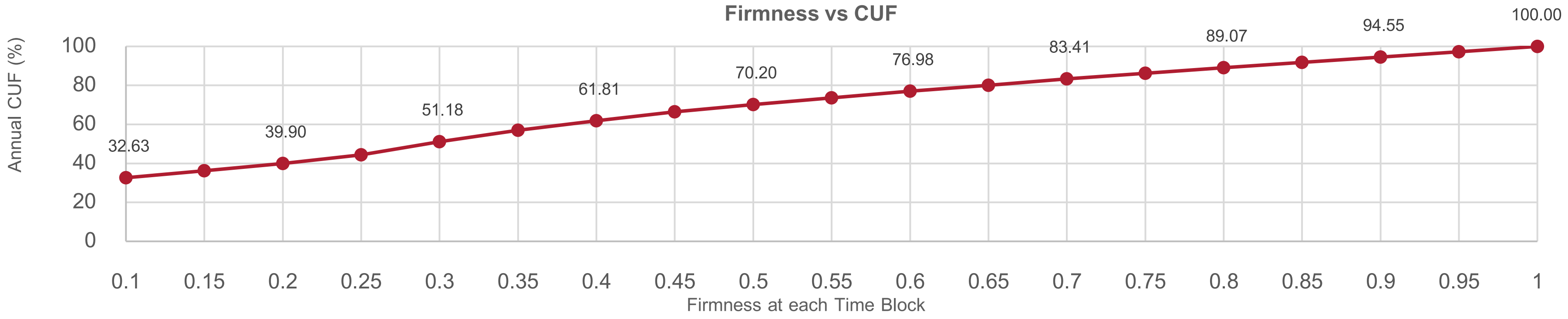
1) **Firmness at every time block (Optimization with Strict reliability)**
   - Supply minimum % in every hour (e.g., 80% each block)
   - Must handle hard(er) hours ⟶ more RE + storage
   - Leads to higher annual CUF and higher cost (LCOE)

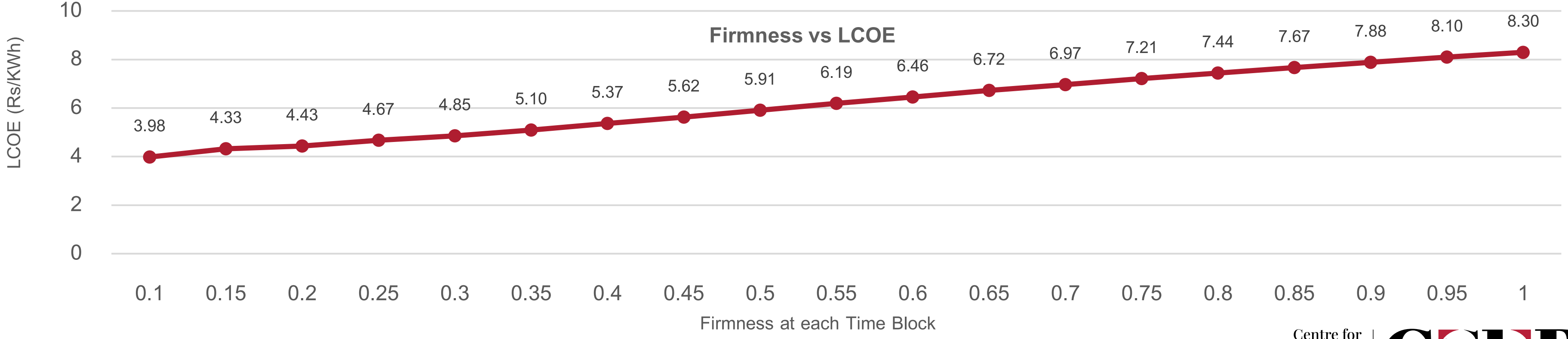
2) **Case 2: Relax worst hours (Cost-optimized)**
   - Allow small % of hours (e.g., 5%) to relax firmness
   - Model avoids most difficult hours
   - Achieves similar annual CUF (~95%) at much lower cost

Same annual energy (CUF) ≠ same reliability ≠ same cost

Hourly Firmness Vs Annual CUF vs LCOE

Increasing firmness raises LCOE because the system must solve the most difficult hours





Case with good solar, instead of national (2023) solar profile
(a reasonable assumption for new projects, in the short run till land limitations arise)

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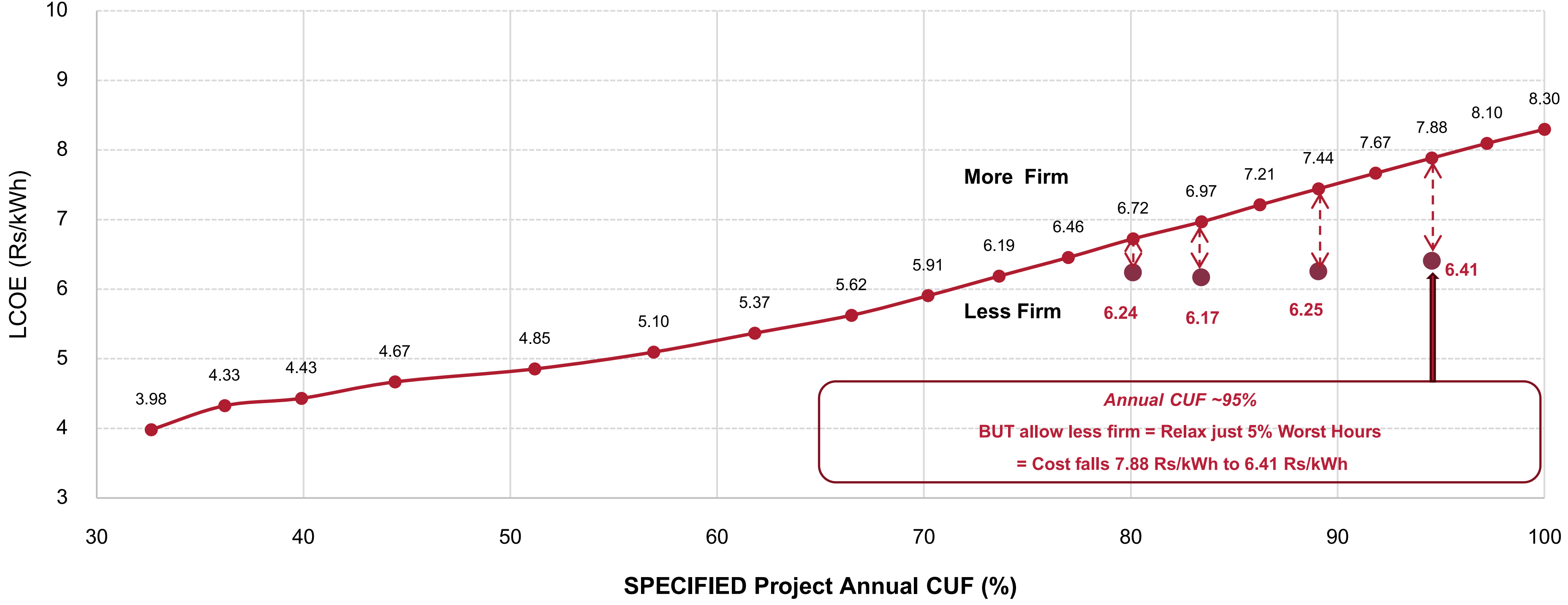
Relax the worst 5% of hours: ₹7.88 falls to ₹6.41/kWh

Nearly the same annual energy (CUF), significantly lower cost



Small flexibility in the worst 10% of hours enables almost the same CUF outcome, with a lower overall LCOE

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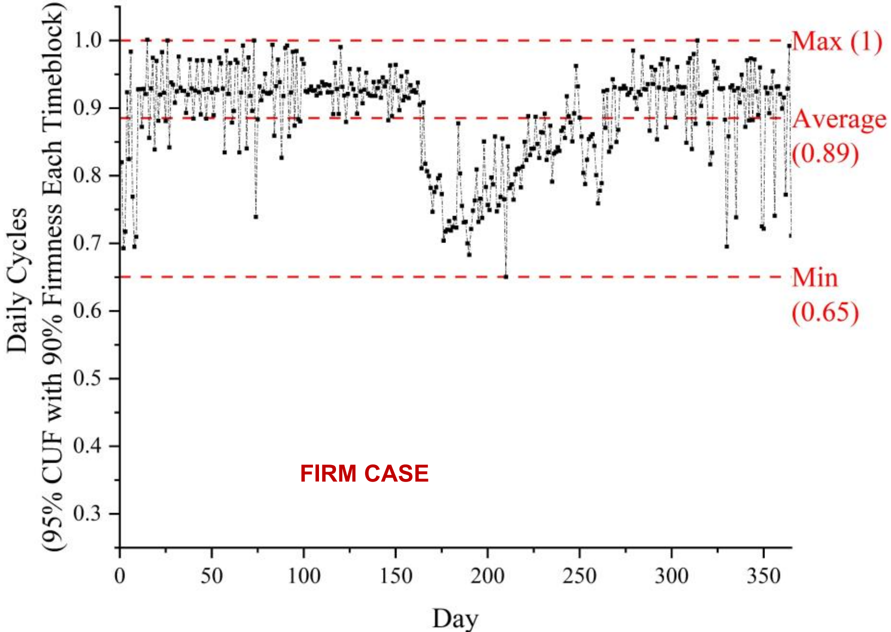
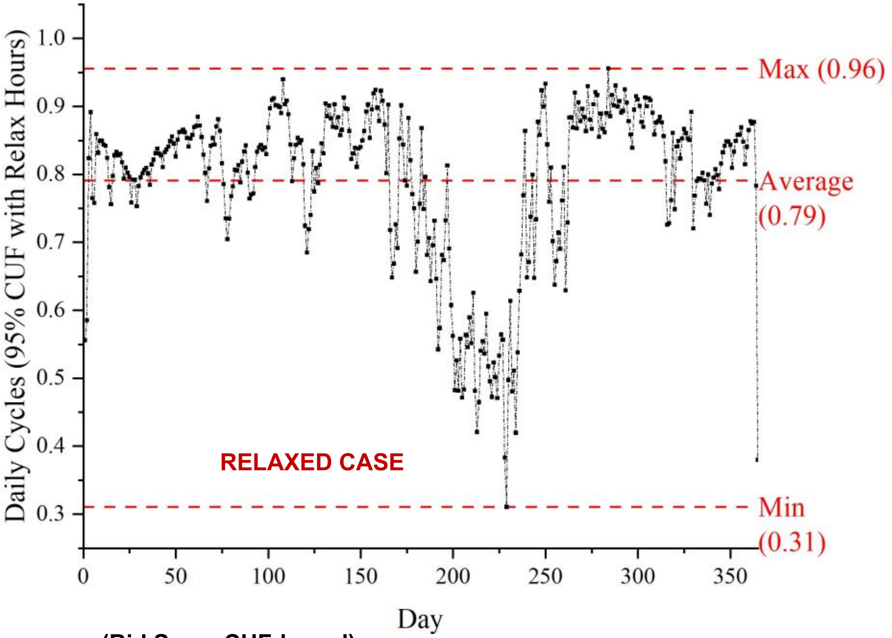
Daily Storage Cycles: Same Annual CUF, Different Storage Use



Bid Spec: Firmness requirement

- Storage effectively provides firm capacity (like built-in reserve)
- Higher cost but high storage utilization and reliability



(Bid Spec: CUF-based)

- Meet annual/monthly energy target
- Grid covers worst hours
- Lower cost thanks to smaller capex (smaller size hardware)

In both cases, the true cost exceeds simple 2-/4-hour tender prices , the difference from "daily use in full" is where the cost appears

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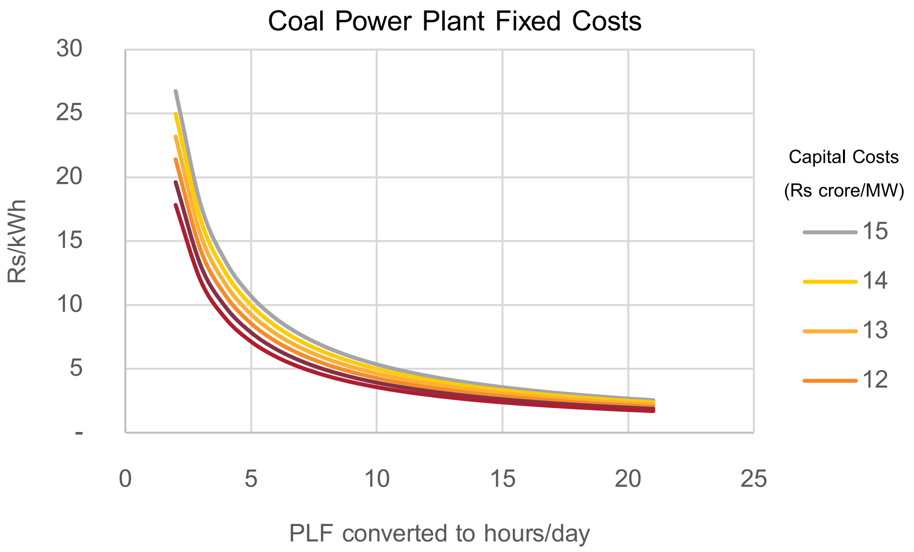
“Coal only runs at ~85% too, so 85% green is equivalent (and good enough)”? *Not quite*

- A popular argument: coal plants are only expected to run at ~85% PLF availability , so 85% coverage from solar + storage is just as good
- That is not an apples-to-apples comparison:
  - Coal downtime is often chosen, with maintenance scheduled in easy seasons;
    RE shortfalls are imposed by weather, often on everyone at the same time (high correlations)
  - New coal can run ~90% of the year, so covering 100% needs only ~10% oversizing
    For solar + storage, covering the last difficult hours needs multiple times higher oversizing
  - Oversized but underused coal saves fuel, but oversized but underused RE/storage systems offer near-zero savings
- Bottom line: “85% from coal” and “85% from solar + storage” are not fungible

“Battery fixed costs already beat coal” misses fuel and usage (duty cycle)



- Comparing only Fixed Costs (FC) charges is misleading
  - Just asking what is the PLF (usage, e.g., equiv. hours per day) is NOT appropriate
- Both Coal and Batteries need a “fuel”
  - Pithead coal can be ~2 Rs/kWh fuel
  - Some of the cheapest (headline) Battery bids IGNORE 2nd cycle charging costs (left to state)

Long duration use raises battery cost, but the more you use a coal plant, FC falls

BUT the challenge is coal cannot easily run as a filler (has a minimum technical output) – we overcome that with a fleet assumption

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Part 4 – The leftover:
Who serves the hours that the bids skip?

- Serving “90% of demand” leaves 10% unmet – but WHEN matters
- Consider 730 hours’ worth of residual (unserved) energy a year (on a normalised 1 kW average demand)
  - Best case: spread evenly, about 2 hours a day. A small battery fixes it.
  - Worst case: concentrated in a few cloudy/high-demand weeks. Needs far more storage, plus extra RE to charge it
- Two ways to fill the gap, each with a cost:
  1. Buy from the power exchange (spot/day-ahead)

     Worries: (1) Is the market liquid enough?; (2) Today’s price spreads are likely to worsen
  2. Run coal or gas as backup

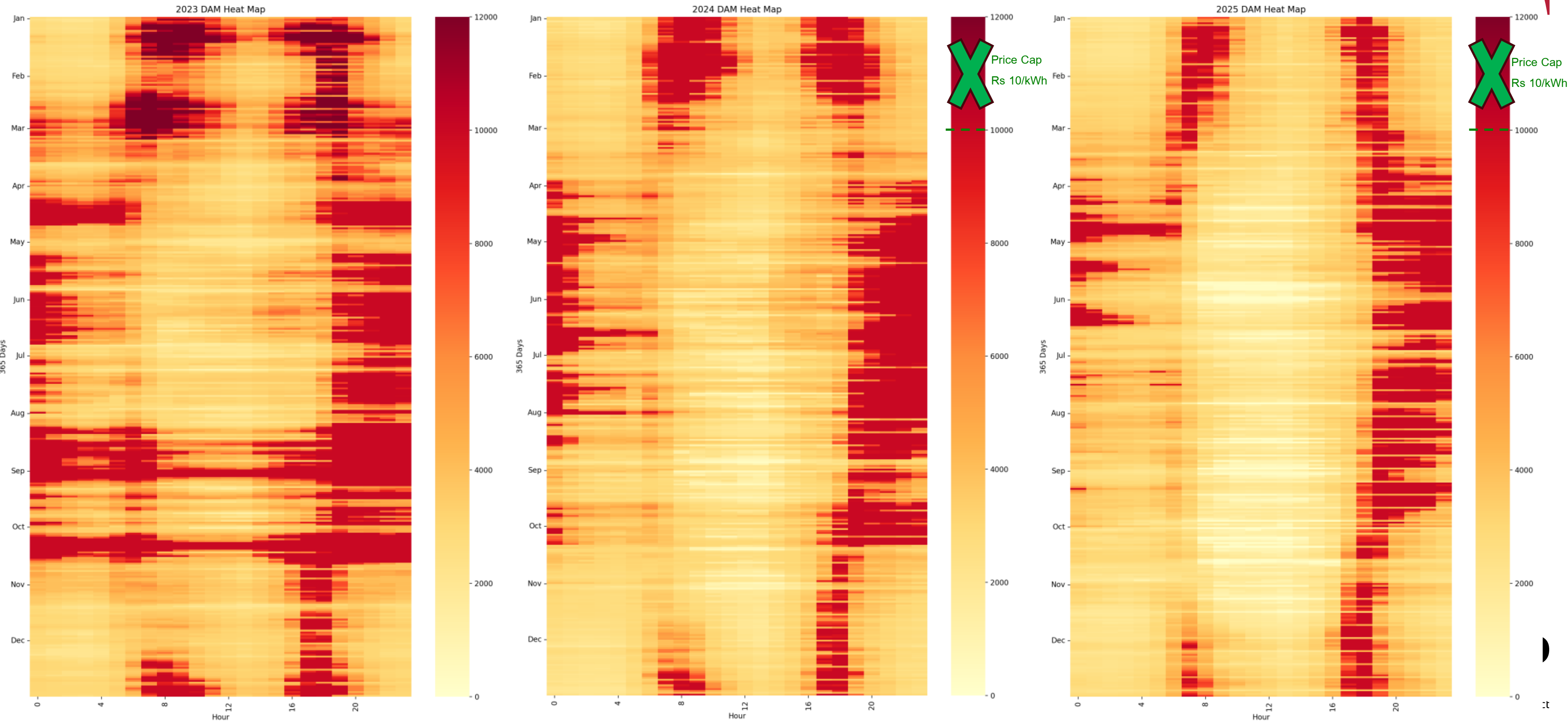
     But coal plants are not designed for stop-start duty, and imported gas supply is insecure (and expensive)

     (Demand flexibility would be the ideal filler)
- We test both using 2023 data, which likely understates the future problem

Option 1 – buy the leftover from the market: prices spike in exactly those hours

Hard to find generators willing to contract at ~10% utilisation today; time-of-day price spreads will widen further

3 years of Day Ahead Market prices from IEX

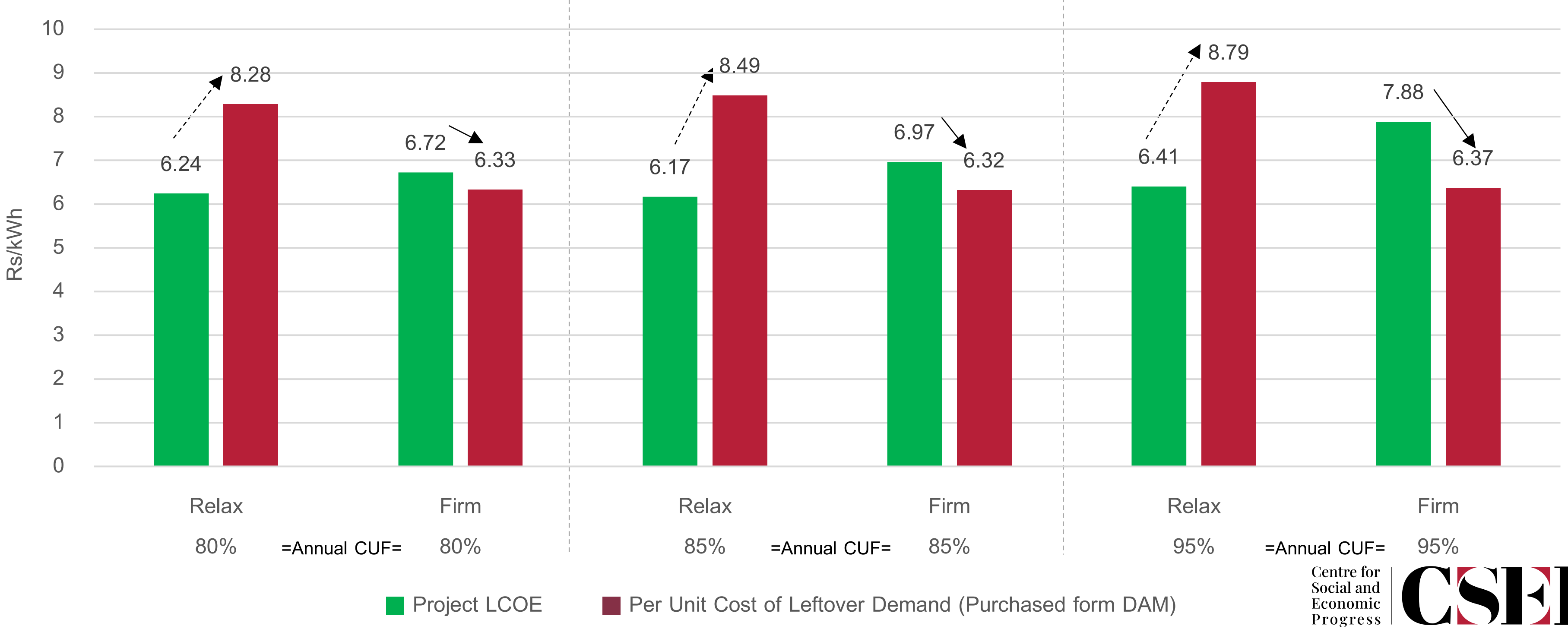


Option 1 (cont.): The tradeoff in filling the gap: Firm vs Relaxed

In relaxed (worst-hour) cases, the per-unit cost of leftover demand exceeds project LCOE, while in strict time-block firmness the leftover cost

However, the overall DISCOM burden depends on RE penetration and system flexibility, implying that a balanced firmness with peaking support is more cost-effective than either overly strict or highly relaxed approaches

More flexibility can lower portfolio costs (more so if DAM prices are modest)



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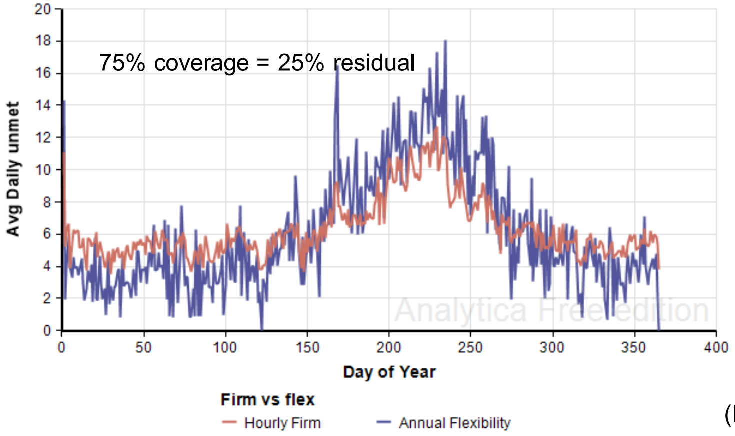
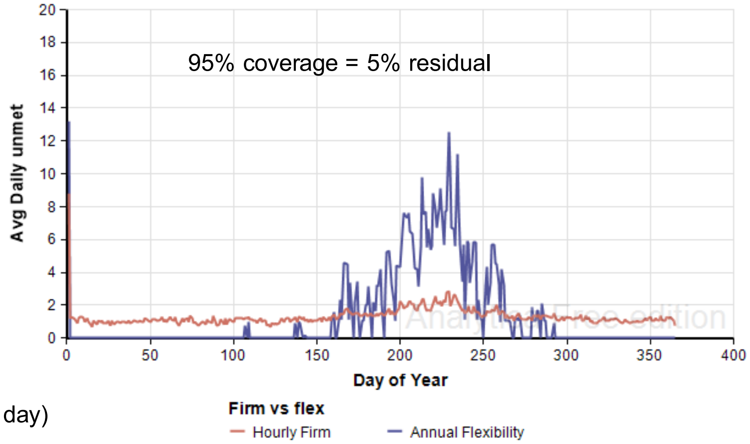
Option 2 – Run new coal or gas as backup (at painfully low utilisation)

- There is great uncertainty in capex and (more so) fuel – and we haven't explored demand flexibility
- Fixed costs depend on usage (duty cycle, or PLF)
- Case: 1 kW normalized demand, for different annual CUF coverages via solar+storage (e.g., 75%/95%) DAILY Balancing Need



(Ignore first day)



- As RE+storage coverage increases, the leftover shape changes for a firmer bid spec;
  More seasonal/bursty residual load is more expensive to meet because it will be underused many days

Demand Coverage via solar+storage:	75%	95%
PLF of residual for Firm (hourly firmness design)	45.89%	42.65%
PLF of residual for Flexible (annual CUF design)	19.42%	4.66%

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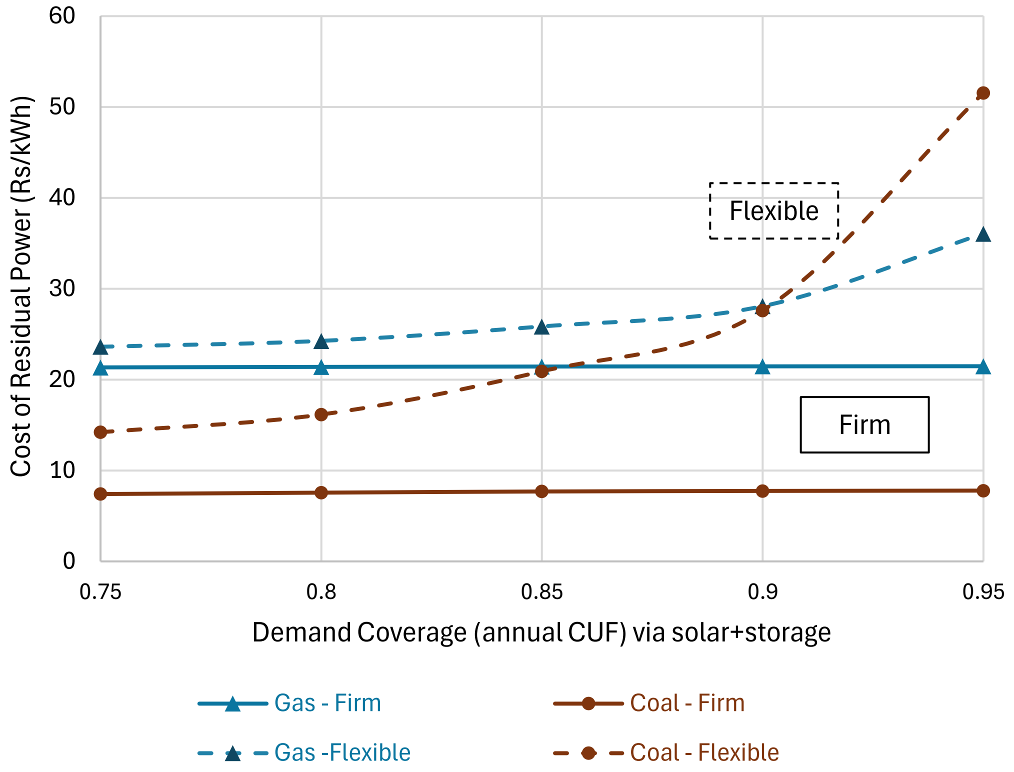
Balancing costs depend on bid type and coverage

Simplified residual demand fixed costs & fuel analysis (with O&M)



- This ignores technicalities of coal plant operations
  - Technical minimum of 55% or 40% is at a plant level – *If we assume coal is a fleet, that can perhaps manage much of this*
- If there is a carbon price, will hurt coal much more than gas

Assumes:

11% WACC; 15 Cr/MW coal capex; 5 Cr/MW capex gas (open cycle);

Coal 25% efficiency; 26% gas efficiency; $15/MMBTU gas

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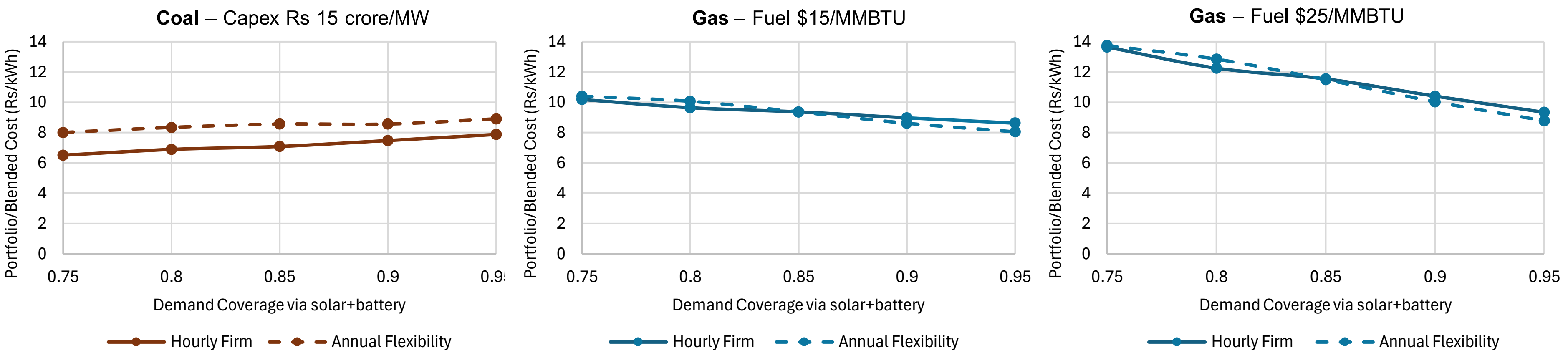
Portfolio level (blended) costs depend on your worldview

Will gas be available, and if so, how expensive?



- **If the expectation is to have coal and not gas, then RE+storage bids should be more firm**
  - Very cheap gas is cheaper AND MORE FLEXIBLE than coal
- India will also need more portfolio analysis (incorporating “rest of grid” (not just new builds like here), demand flexibility, etc.)
- **Bottom line: Cheap solar + battery needs expensive balancing**

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Highlights of Key findings

- Storage is still important and critical for India – we are way behind other countries
  - It's just that storage isn't yet ready to "do it all"
- Cheap storage of today is based on incomplete accounting
- A more nuanced full-grid analysis which factors in both other supply options and demand flexibility will show the full system costs
  - Any such analysis will be assumption-laden – technology learning curves, costs of capital, fuel costs, etc.
  - But the balancing numbers shown (for residual demand) are indicative of the trends and issues: *lack of firmness compared to hourly demand is a real cost for discoms*

Conclusions and Policy Implications

India is not choosing between cheap and expensive power, it is choosing where and how the cost of reliability is paid

- It is a false analysis to claim RE+Storage can obviate all new coal
  - Current bids are cherry-picking demand coverage and artificially cheap
    - Even partial firming (for 75% - 95% annual coverage) raises costs measurably (exceeding Rs 7.5/kWh – with best solar profiles/sites)
    - Even worse, the balancing of the residual demand is non-linearly expensive
- One cannot apply the same modelling for coal costs vs. RE costs
  - E.g., 85% demand fulfilment isn't the same in both cases – when you can deliver is different
- Current storage bids leave enormous flexibility for RE developers – whose cost is borne by the DISCOM
- There are multiple ways to achieve a chosen annual output
  - With hourly firmness – raises project costs but lowers system costs elsewhere
  - With flexibility to the developer – looks cheaper on paper but raises costs elsewhere

Conclusions and Policy Implications (2)

Storage in current bids helps compared to "vanilla" solar, but its interpretation needs system-reality alignment

- The exact combination of how flexible vs. firm depends on a range of assumptions
  - Modest clean energy flexibility lowers costs measurably – but needs complementary alternative supply
    - Small flexibility in the worst hours gives disproportionate cost savings
    - Relaxing even ~5% of hardest hours reduces LCOE significantly with zero impact on annual energy (e.g.,: 7.88 Rs/kWh to 6.41 Rs/kWh for 95% annual CUF)
    - This leftover can be met through demand response/flexibility (cheaper than "peakers" like open cycle gas)
      - Note: Some FDRE and peak-period bids today have a whole month allowed for relaxation, plus monthly averaging
- Ignoring the residual demand is risky
  - The less you have leftover to supply, the inherently more expensive it will be
    - The shape of the leftover really matters
  - Market (DAM) prices hint at the problem – which will get worse over time (greater ToD spread – e.g., "Necklace Curve" seen in 2026)

Ultimately, there is enormous value to adding more storage and RE

…but not (yet) getting rid of coal entirely

Open policy questions

- What is India's peaker plan? It is not about storage alone
- Pace of adding new capacity (including factoring in curtailment)?
- Why are coal power plants so expensive capex?
- Performance of batteries in real-world heavy cycling operations (high temps = more Auxiliary Consumption/O&M)?
- Are we facing a "valley of death" of coal PLFs? (for unmet demand after RE+storage)?
  - If very low PLF, then any peaker is OK (and will be expensive per unit)

    vs

    If high PLF, coal is optimal = "baseload"

    … are we in between?
  - A paper "sweet spot" is not enough: there is directionality based on where you start. If you need some coal, and build for it, does that then displace new RE (marginal cost comparisons)?
  - *Coal won't be the best answer for very low PLFs, but we're not at that point any time soon*

What this study does not do (limitations and clarifications)

- This is NOT a full grid optimization analysis, where existing power plants can play a role, specifically:
  - Wind (is partly seasonal)
  - Hydro is a peaker (but not growing commensurately with demand)
  - Some slack exists in coal plants to meet demand, and there is also some (short-term) possibility to lower coal output without reaching mandatory surplus RE (= curtailment) [assuming sufficient transmission]. HOWEVER, in the longer run, this will become less relevant.
- We do not design the battery for (daily) arbitrage – there is the possibility to make some money by strategically charging the battery when overnight power exchange prices are low, increasing the usage in the morning
  - Our analysis was from the perspective of a discom meeting demand
  - One can increase the cycle usage of the battery to displace coal from unused cycles (if RE is sufficient) – up to a point
- We do NOT factor in issues of grid costs like transmission or coal plant part load operation/ramping; we do, however, factor in lower efficiencies for coal if used for meeting residual demand

Thank You

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