Drivers to Coal Phase-Down in India: Part 1 - Battery Cost Declines

How battery cost declines can help India's power sector push through different stages of phasing down coal power

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Contents

About

This report is part of a series examining key drivers to accelerate India's power system transition over the next decade. It aims to identify conditions conducive to accelerating decarbonisation of the power system in India. The focus is on highlighting priority areas for Indian policymakers and global stakeholders to prioritise.

This report focuses on BESS cost decline as an important driver for reducing coal dependency in the Indian power sector. It explores the least-cost pathways for the supply and storage mix required to meet future electricity demand from 2024 to 2032. The analysis evaluates various scenarios of battery energy storage system (BESS) cost declines and their impact on coal generation and capacity buildup.

We conducted our analysis using Ember's PyPSA-based co-optimization model for India, which determines the least-cost generation and storage mix from 2023 to 2032. This model helps explore least-cost optimised pathways for India's power system transition.

Highlights

83%

Highest share of renewable energy in India's grid during daytime in 2032, in the least-cost pathway

15%

Average annual cost declines in BESS costs needed to limit coal capacity addition to NEP levels

6 million

The cost in Rs/MWh for BESS to be preferred over any new coal capacity

Executive summary

Falling battery storage costs can unlock India's coal phasedown

Battery Energy Storage Systems (BESS) costs, excluding the cost of finance, need to fall 15% annually on an average to avoid new coal capacity additions after 2030.

At COP26, India announced its ambitious target of achieving net-zero emissions by 2070. To reach this goal, India must transition to a low-emissions power sector as soon as possible. Currently, nearly three-quarters of India's electricity is generated from coal, making the phasedown of coal generation crucial for staying on track with the net-zero target.

What could a "coal phasedown" actually mean in the Indian context? This report outlines the stages of coal phasedown: initial period of slowing growth in annual coal generation as renewable energy (RE) is increasingly integrated, followed by a period of plateau in coal generation as RE plus storage becomes cheaper than new coal plants, and ultimately, an absolute decline in coal generation as RE plus storage outcompetes the marginal cost of existing coal capacity.

While India is currently making significant strides in solar, timelines for peaking coal generation or coal phasedown are unclear, partly due to the uncertainty regarding storage costs. Building more storage capacity fast enough is crucial to progress through these stages of coal phasedown.

With India's electricity demand also projected to grow by nearly 6% in the next decade, power system planning becomes critical and expanding the power system in a cost-effective manner is essential. New modelling in this report presents a least-cost pathway for India's power sector, examining the sensitivity of a least-cost optimised (LCO) model to different battery project costs. It highlights the necessary declines in battery costs required to advance through the stages of coal phasedown.

01 RE can meet up to 83% of daytime electricity demand in 2032, but only 38% in non-solar hours

In 2023, RE penetration was around 34% during the middle of day in sunnier months. In the LCO pathway, India would need to build up to 375 GW of solar by 2032, which will drive up the RE level in the grid to around 83%, while non-fossil generation can even touch 100% during some solar hours in the year. In contrast, the highest RE penetration during the non-solar hours will see much less increase, from 21% in 2023 to 38% in 2032. This is mainly because storage growth becomes a limiting factor once solar's share in the power mix crosses 25%.

02 Coal generation can plateau till 2032 if battery storage project costs continue to fall at current rate

India's on-grid coal generation stood at 1265 TWh in 2023. If the battery project costs in the country fall at 7% annually (average decline seen in the last four years), the LCO pathway will see coal generation hovering around current levels till 2032. But entering this plateau stage of coal phasedown depends on India building RE fast enough (~43 GW of solar and wind annually on average). If the battery project costs decline more aggressively, the LCO pathway shifts to unlock more solar integration into the grid and may even result in structural decline in coal generation before 2032.

03 Battery storage project costs need to fall by 15% annually to avoid any new coal capacity additions after 2030

India's LCO pathway with a 7% annual decline in battery project costs will still necessitate building more coal capacity, reaching 286 GW by 2032, despite coal generation plateauing at current levels. This is mainly because BESS is not cost effective to demand across all the non-solar hours. But if battery project costs fall by 15% every year till 2032, the LCO pathway will limit coal build to 260 GW which is the projected capacity as per the 14th National Electricity Plan.

04 No new coal additions might be needed as soon as BESS costs fall to half of the current levels

BESS costs, excluding the cost of financing, currently stand close to Rs 13 million/ MWh. The LCO pathway indicates no new coal additions might be needed if this drops to around Rs 6 million/MWh. While recent declines in BESS costs have been significant, they need to fall by more than 50% from current levels for the least-cost pathway to favour no new coal additions, especially for meeting non-solar demand.

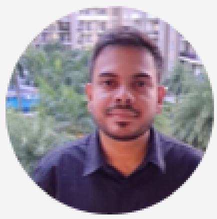
Overall, the cost optimal pathway for India's power transition is highly sensitive to the rate at which battery project costs decline. If they fall 7% annually, India's coal fleet will already see its utilisation factor reducing from 68% in 2023 to 50% in 2032. If BESS costs fall faster than anticipated, any new coal planned capacity faces severe lock-in and underutilisation risks.

Policy interventions facilitating battery cost decline, such as Viability Gap Funding and measures to optimise utilisation of existing coal capacity could be alternatives to avoid committing to more coal capacity.

Planners will now need to consider strategies for shifting solar generation to non-solar hours to ensure that the pace of the transition does not slow down. Therefore, while declining battery storage costs are crucial, it's also important to focus on increasing annual renewable energy capacity, securing necessary financing, and enhancing coal plant flexibility.

Neshwin Rodrigues

Electricity Policy Analyst - India, Ember



Energy storage holds the key for decarbonization of electricity generation; reduction in cost of various storage options would accelerate the energy transition in economies.

Mr A K Saxena

Senior Director, Electricity and Renewables, TERI

Accelerated growth in solar and wind, development of pumped hydro projects, and cost-competitive low-carbon technologies like BESS are essential for India to avoid new coal capacity. Additionally, flexible operations in coal plants and rapid battery cost declines will enable shifting solar generation to non-solar hours, replacing coal-based generation.

Nayeem Khan

Research Associate, TERI

Chapter 1 | Clean power transition

What could coal phase-down mean for India's power system?

India’s journey to net-zero by 2070 hinges on strategic phasing down of coal-based electricity, which could involve three critical stages

India has set a target to achieve net-zero carbon emissions by 2070, as announced by the Hon’ble Prime Minister at the COP26 summit. Despite having one of the lowest per-capita emissions, India is the third-largest GHG emitter in the world. The Indian power sector, as the single largest CO2 emitter, contributes approximately 50% of the total CO2 emissions, making it a critical area for transition planning. To achieve economy-wide net-zero emissions by 2070, the Indian power sector will need to reach net-zero emissions much earlier.

In the financial year (FY) 2023-24, electricity demand grew by 7.8%, while the country recorded its highest-ever peak demand of 250 GW on May 30, 2024. With electricity demand expected to increase by around 6% annually over the next decade, power sector transition planning must also ensure affordable and reliable electricity supply.

Understanding options to reduce reliance on coal power is essential for India to move towards achieving net-zero in the power sector. The process of phasing down coal generation in India could be understood by looking at how integration of RE and storage impacts the need for coal power over time. This could be split into three stages.

Stage 1: Period of slowing growth in coal generation

In this stage, the growth of coal-based electricity generation slows down significantly as RE is increasingly integrated. Coal’s share in the generation mix decreases, though absolute coal generation might still increase to meet non-solar demands, but at a slower rate. This stage is reached when the Levelized Cost of Electricity (LCOE) of RE without storage becomes much cheaper than the LCOE of new coal generation and, in many cases, cheaper than the marginal cost of existing coal. Annual RE additions need to significantly increase to ensure that the growth in absolute coal-based generation slows down.

Stage 2: Period of plateau in coal generation

In this stage, the absolute generation from coal increases marginally or plateaus. This occurs when the LCOE of RE plus storage becomes less than the LCOE of new coal, but not cheaper than the marginal cost of existing coal. This leads to minimal to no growth in absolute coal generation terms.

Stage 3: Period of absolute decline in coal generation

In this stage, the LCOE of RE plus storage becomes cheaper than the marginal cost of existing coal, allowing it to displace coal generation even during non-solar hours. New RE plus storage capacity will be added incrementally whenever financially viable. This displacement can also occur as existing coal generators reach the end of their respective lifetimes.

In India, the timelines for phasing down coal generation have been unclear due to several uncertainties, especially regarding storage costs, demand growth, and the costs of solar and wind energy. Socioeconomic factors such as job creation, livelihood, state finances, and manufacturing advancements also impact the transition's pace and feasibility.

The cost-effectiveness of storage is an important factor in India's decision to commit to no new coal additions and investing in solar plus storage could be the least cost option going forward. The fewer long-life coal-fired power plants India builds from now on, lesser the lock-in effect will be, resulting in a faster and cheaper coal phase-down process, particularly as India enters the third phase of phasedown.

Pumped hydro storage plants (PSP) could be an option and currently is the most cost effective amongst the energy storage systems. TERI's recent study spelt out the ways in which large-scale PSP capacity can contribute to India's 500 GW of non-fossil fuel capacity by 2030 target. The government has also come up with guidelines to promote pumped hydro in India. But the growth in the next decade (the time-horizon of this study) will depend on the extent of projects already in planning and under-construction, so the study does not explore sensitivities around PSP costs. Thus, this report mainly focuses on battery cost declines, and its implications on the phase-down of coal-based generation.

Chapter 2 | Least-cost optimised transition

Pace of supply-side transition could be hindered by lack of cost-effective storage

In a LCO pathway for India's power sector, solar will dominate growth in electricity generation, but the cost-effective storage options become crucial, particularly after solar energy crosses 25% of the energy mix.

Base case findings

In the base case of the LCO pathway, India's power sector supply mix is projected to change significantly over the next decade, with solar growth playing a major role. Solar capacity is expected to increase from 84 GW (as of May 2024) to 375 GW by 2032. This projected growth is driven by increased in electricity demand and the cost-competitiveness of solar, despite policies like the Basic Customs Duty (BCD) increase and the introduction of the Approved List of Models and Manufacturers (ALMM), aimed at boosting domestic manufacturing, have increased costs in recent years.

To achieve this level of solar growth, India will need to add around 38 GW of solar capacity annually on average from 2024 until 2032. For context, India is projected to add around 25 GW in FY 2024-25, and in recent years has added between 10 and 14 GW annually. With a solar pipeline and underbidding capacity of around 96.6 GW (as of Q1-2024) likely to be commissioned in the next 3-5 years, the annual addition is expected to be at least between 20-30 GW in this time period.

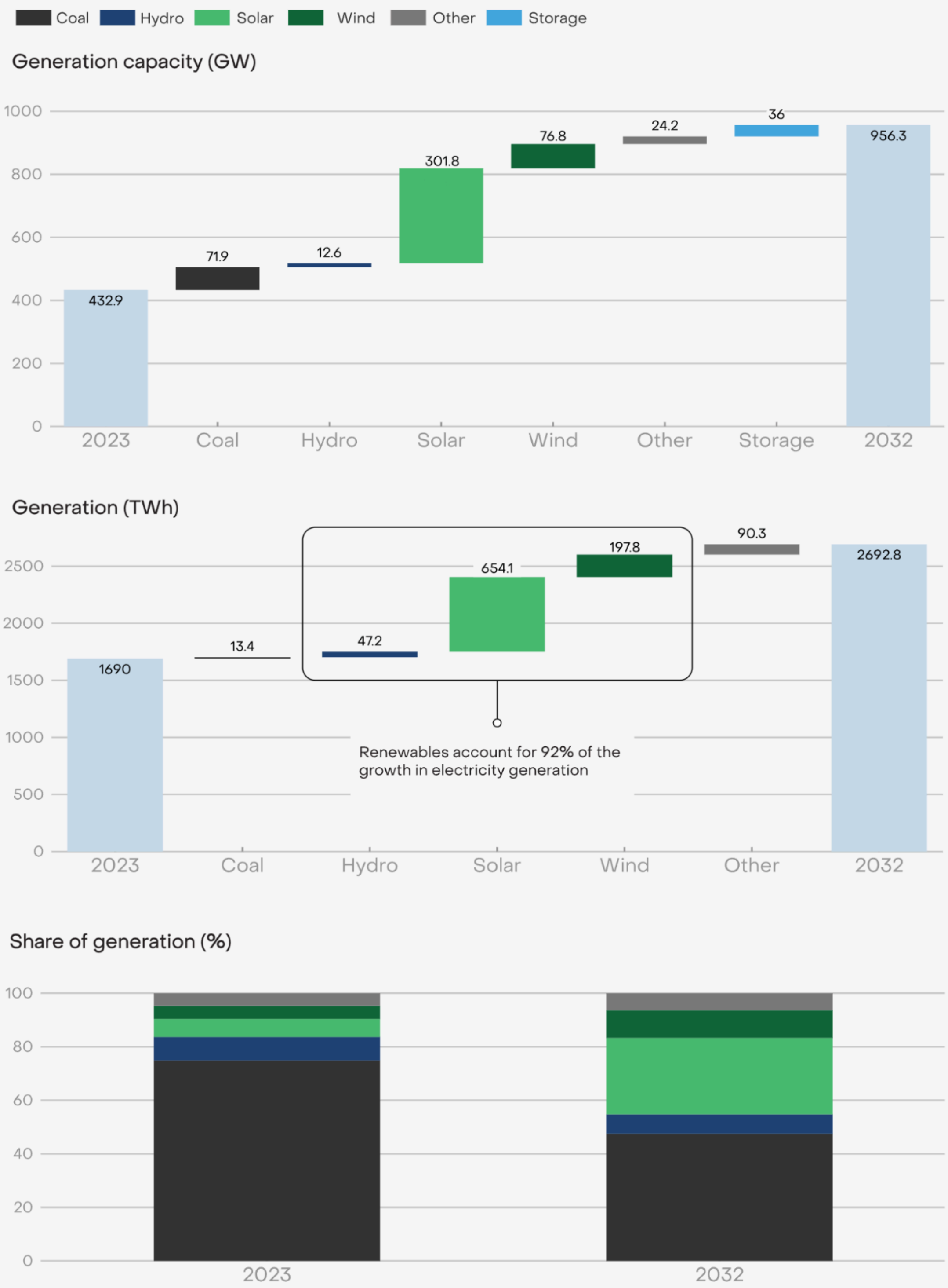
Key projections and assumptions in the LCO base case

- Electricity demand of 2692 TWh and a peak demand of about 398 GW by 2032
- Conservative solar and wind capital cost assumptions, which are not assumed to decrease until 2032 due to recent developments
- Battery Energy Storage System (BESS) costs are projected to decline at a rate of 7% annually, reflecting the average decrease over the past several years.

Detailed assumptions and rationale are available in the methodology section and datasheet.

The LCO transition pathway for India's power sector sees significant solar growth

Actual supply mix and supply mix in LCO pathway



Source: Ember's India electricity data explorer, 2032 supply mix as per Ember-TERI least cost optimized (LCO) pathway

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In the base case, wind capacity also grows steadily, increasing from 46 GW (as of May 2024) to around 121 GW by 2032. However, with only 13 GW in the pipeline and under different stages of bidding, aligning with this pathway depends on whether India can successfully add a little more than 8 GW (4 GW projected for FY2025) annually until 2032.

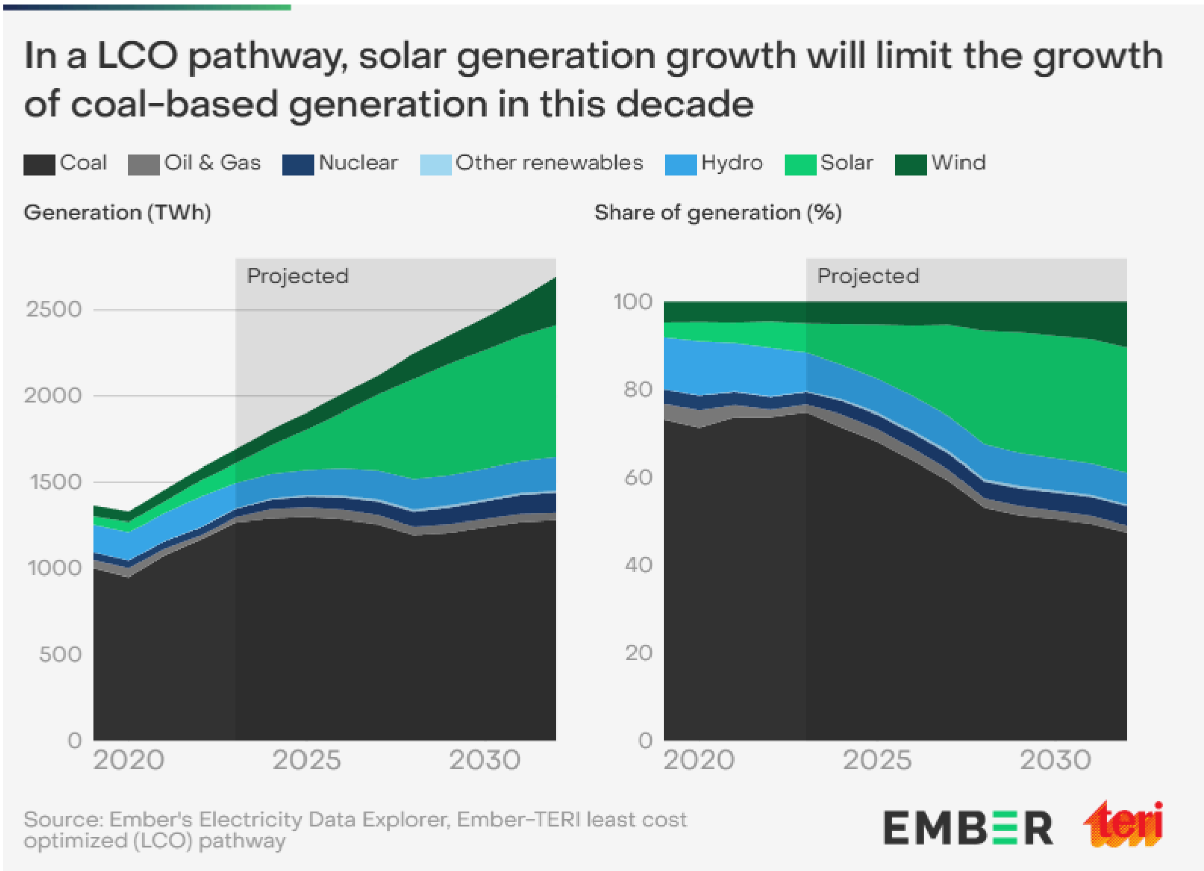
Despite being cost-effective, hydro capacity buildup is expected to increase from 47 GW (as of May 2024) to only about 64 GW in 2032. The capacity buildup is constrained by the current pipeline and planned capacity in India, considering construction and planning time horizons for new large hydro capacity. Despite recent flash floods resulting in disruptions, the Government of India is confident that the existing pipeline capacity of around 15 GW is likely to be commissioned by 2032.

The base case also indicates an increase in coal generation capacity. With approximately 27.6 GW of coal capacity in advanced stages of construction, expected to be operational by 2027, the total coal capacity could reach at least 240 GW. An additional 54 GW in the pipeline at various stages of planning and development. Coal capacity could potentially reach around 286 GW by 2032 in the LCO pathway, which to some extent, aligns with the government's plans to build an additional 80 GW of coal capacity by FY 2031-32. But it is important to note that his additional coal capacity could lead to severe lock-ins, especially given the recent trend of falling battery storage costs.

One main reason for the projected increase in coal capacity is the relatively low buildup of BESS, with only 44 GWh by 2032, which is 192 GWh lower than the National Electricity Plan (NEP) target. The projected annual decline of 7% in BESS costs was found to be insufficient to make battery storage combined with renewable energy more cost-effective than new coal-based capacity for meeting demand across all non-solar hours. Additionally, the expected growth in pumped storage plants (PSP) will not be adequate. Initiatives such as the Production Linked Incentives (PLI) and Viability Gap Funding (VGF) will therefore be crucial for not just increasing battery storage capacity but also to phasing down coal.

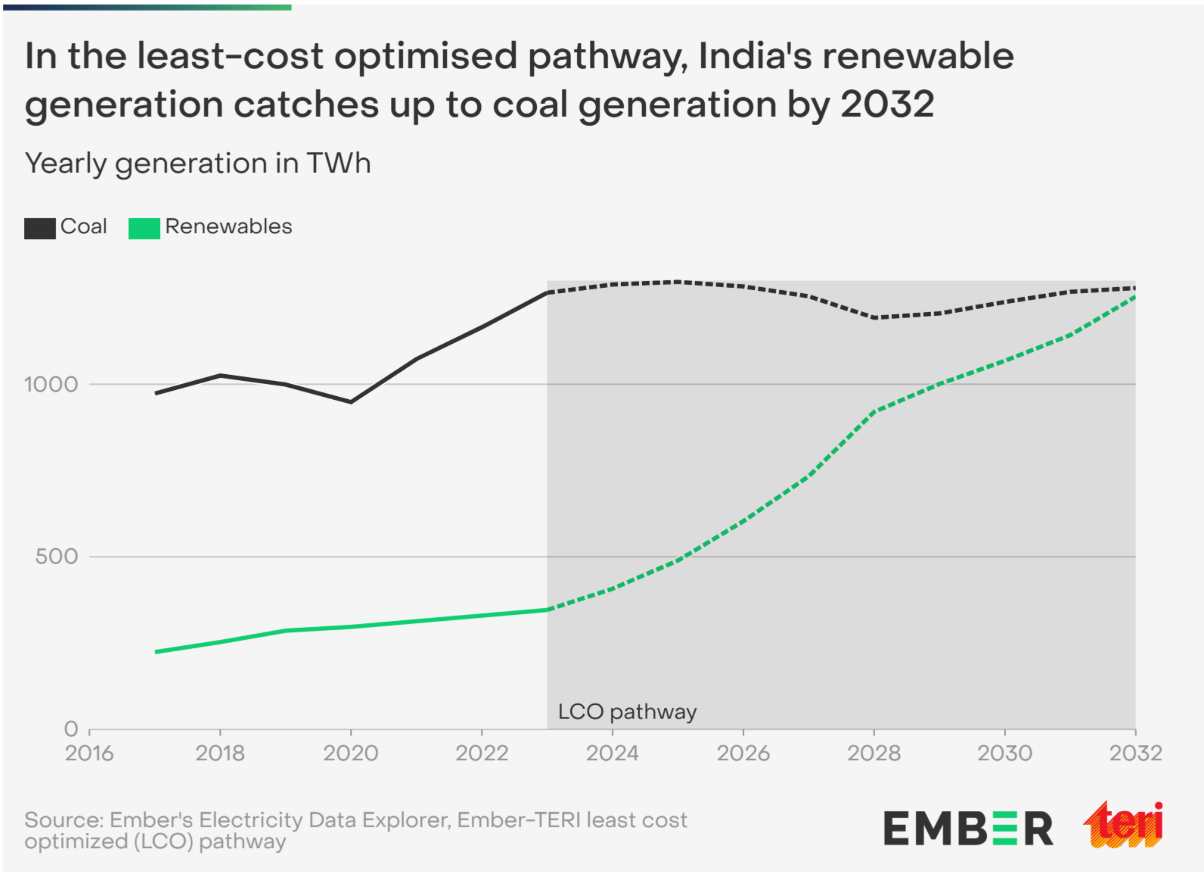
One thing that is very clear, however, is that renewables will account for a majority of electricity generation growth till 2032 in the LCO pathway. Total electricity generation in the base case increased by 989 TWh from 2023 levels to meet rising demand. Solar and wind met most of this growth, with solar alone contributing about 66% (~653 TWh) of the total increase. Combined renewables, including solar, hydro, wind, and bioenergy, accounted for approximately 93% (918 TWh) of the growth in electricity generation by 2032.

This trend may begin in FY 2024-25, with solar capacity projected to reach around 25 GW, potentially increasing generation by approximately 50 TWh (assuming a CUF of 23%). A 6% growth in electricity demand will increase electricity demand by about 102 TWh, which means solar can potentially meet about half of the additional generation this financial year.



Renewables will likely account for increasingly bigger shares of total electricity generation growth in the coming years if solar capacity additions increase by 36% annually. In the base case, the total RE generation can even rise enough to nearly equal coal based generation by 2032.

On the other hand, coal generation in 2032 will remain close to the current level despite the capacity addition. This will result in a significant reduction in the Plant Load Factor (PLF) and an increase in the per-unit cost of electricity from coal plants. Any shortfall in nuclear or hydro generation is likely to lead to an increase in coal generation and installed capacity.

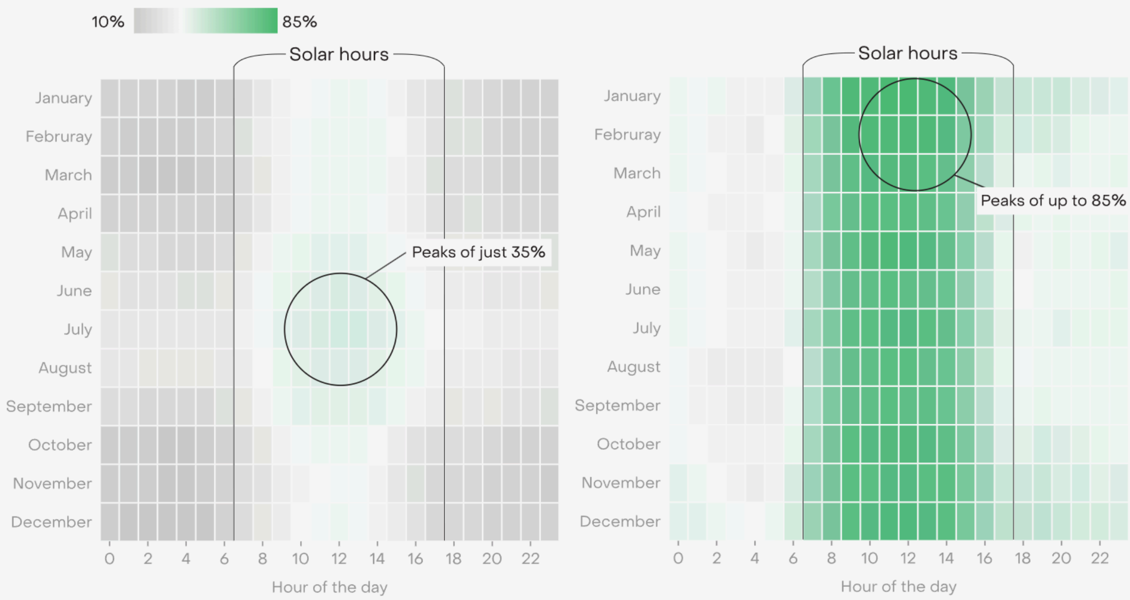


Limits to faster RE integration in the grid

With the growth in solar, the share of RE in the Indian grid varies marked between solar and non-solar hours. In 2023, the highest renewable energy share in the grid was 34% during daytime and about 21% during non-solar hours. By 2032, in the base case, the renewable generation reaches as much as 83% during the day, but non-solar hour penetration reached only 38%. Despite the cost-effectiveness of solar, a 7% decline in battery costs annually would displace only a limited amount of coal during non-solar hours.

India's renewables share can touch 83% during solar hours by 2032, but reach just 38% during non-solar hours

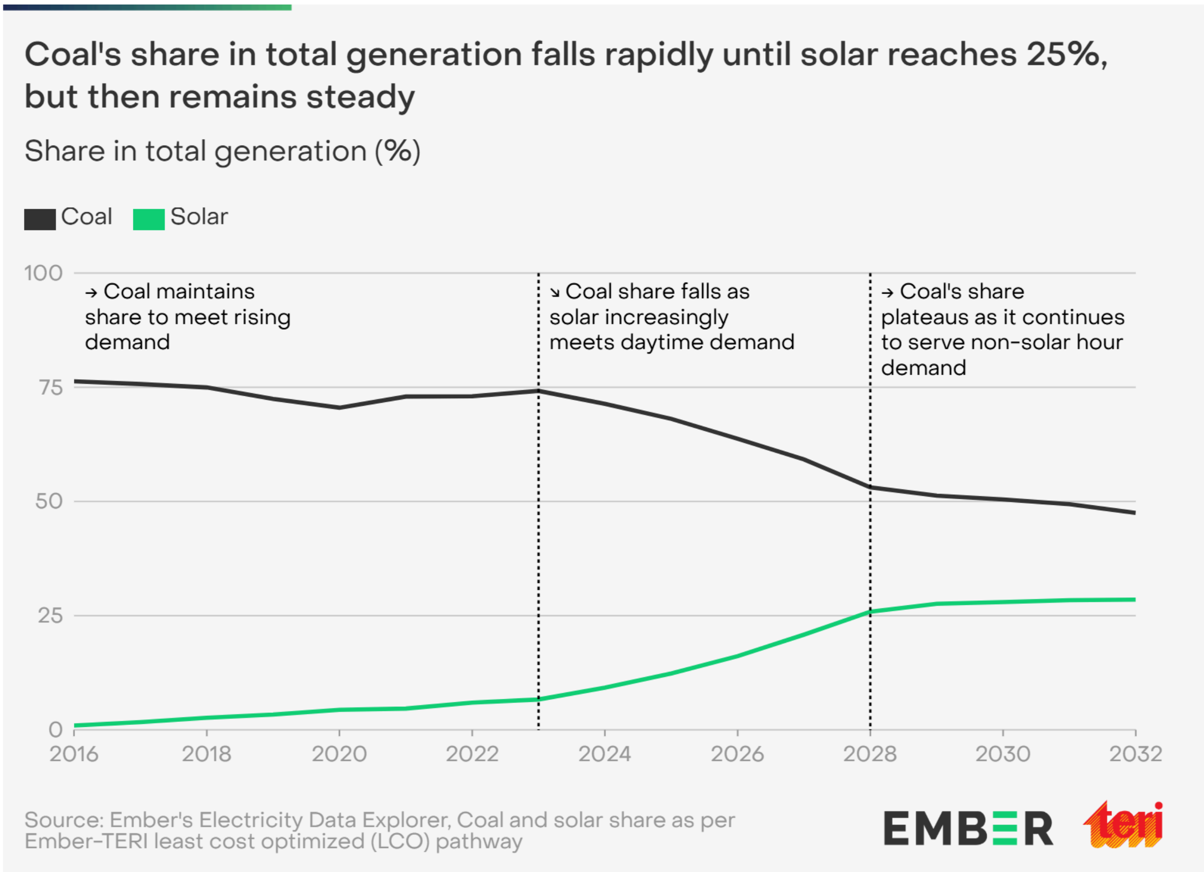
Average % of RE in grid at different hours of a day in 2023 and 2032 (LCO pathway)



Source: 2023 RE share estimates based on Merit India, 2032 RE share as per Ember-TERI least cost optimized (LCO) pathway
Solar hours assumed to be from 7:00 to 17:00, renewables include large hydro

Ultimately, the key to reducing reliance on coal would be to find ways to meet the electricity demand across all the non-solar hours. In this regard, it is important to note two key aspects. Firstly, a significant reduction in battery storage costs can be crucial for shifting more solar generation to non-solar hours. Secondly, if demand continues to grow primarily during solar hours, increasing solar capacity could be beneficial.

In the base case, coal's share of total generation declines rapidly until 2028, especially as solar starts meeting an increasing amount of the electricity demand, especially during the daytime. However, after a period of time, growth of solar will be limited by the ability to cost-effectively shift solar generation to the non-solar hours through storage. This plays out in the model as well, as the reduction in coal's share slows down between 2028 and 2032. This slowdown aligns with solar generation reaching about 25% of the total generation. After this point, the role of storage becomes particularly important. Without adequate cost-effective storage capacity there will be a slow down in the reduction of coal's share.



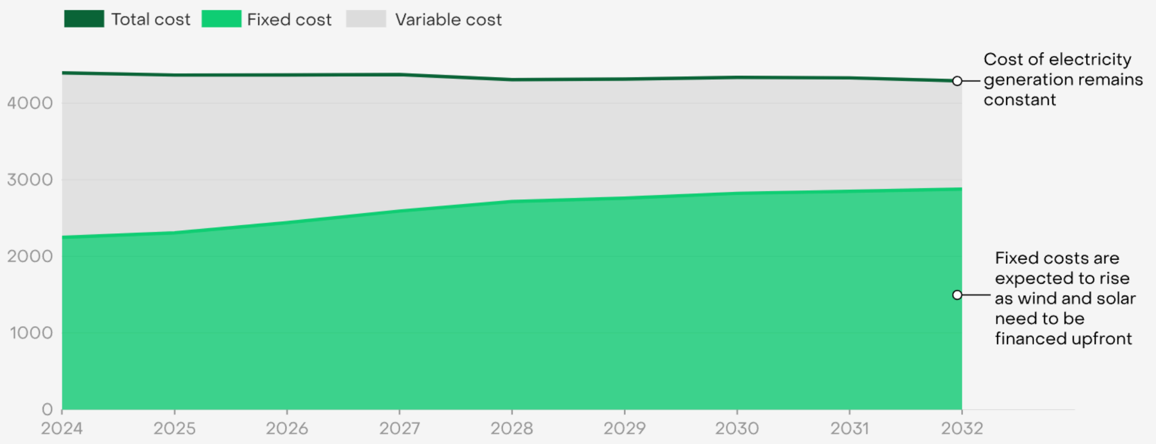
After 2028, the 7% annual decline in BESS project costs may not be sufficient to make solar plus battery storage more cost-effective than new coal generation for meeting night-time demand. Without more substantial cost reductions in battery storage, solar energy cannot fully replace coal during non-solar hours, resulting in a slower coal phase-down after 2028.

Additionally, the cost and availability of financing for RE and storage are likely to become increasingly critical. Renewables growth could result in a modest 3% reduction in nominal generation costs. This is because solar-based generation is cheaper than the variable costs of many existing coal-based power plants. This cost advantage is a significant driver for transitioning away from coal, aiming to lower electricity supply costs and reduce emissions. However, the overall reduction in generation costs is limited by the underutilization of coal capacity.

On the other hand, the fixed component of generation costs is expected to rise. Renewables like solar and wind incur primarily fixed costs due to the lack of fuel expenses. As these renewables become more prevalent, fixed costs will increasingly influence total generation costs. Therefore, the availability and cost of financing will be critical to successfully transitioning to renewable energy in India.

Cost of electricity generation in the LCO pathway will remain at current level but higher capex will make financing crucial

Per-unit fixed, variable, and total cost in Rs/MWh



Source: Ember's analysis of system costs in the Ember-TERI least cost optimized (LCO) pathway

Chapter 3 | Necessary conditions

Prerequisite for India to align with the LCO pathway

To align with the LCO pathway, India must meet investment requirements, significantly increase capacity additions, and enhance the operational flexibility of existing plants.

As solar generation grows, coal-based plants must adapt to flexible operation modes, often requiring costly modifications. The effective utilisation of existing coal plants and improvements in their flexibility are essential. Without significant investments in storage, the growth of solar beyond 25% share in the mix will be limited. Adequate storage is needed to manage demand during non-solar hours and support a more extensive renewable energy share.

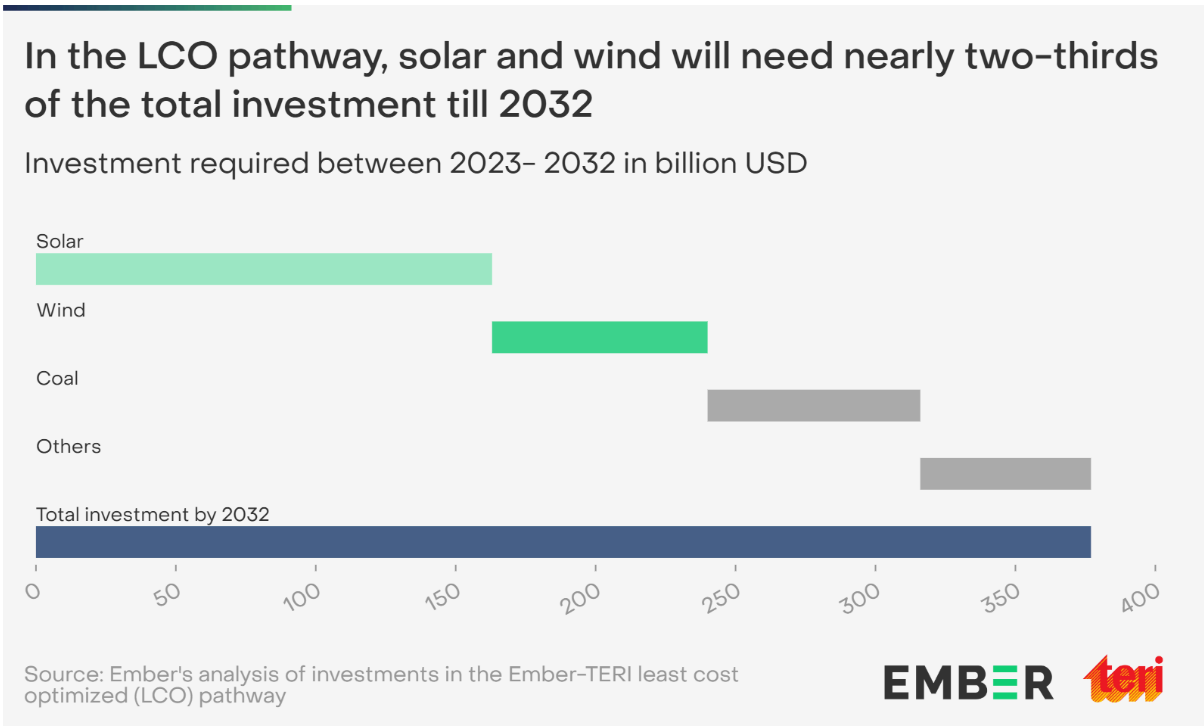
In the base case scenario, India's successful energy transition depends on significantly ramping up annual additions of solar, wind, and pumped storage projects (PSP). To align with the LCO pathway, India must add about 38 GW of solar and 8 GW of wind capacity on average between 2024 to 2032. Additionally, the plan includes adding around 27 GW of pumped storage capacity by 2032. Achieving these targets is crucial for the successful transition outlined in the base case scenario.

On the other hand, policy makers would need to also aim to make the power sector investable, given the level of investment required in the near future. In the base case scenario, 377 billion USD will be required on the supply side in generation and storage capacity alone. with additional investments required for transmission capacity and improving distribution infrastructure.

Despite the recent uptick in investments in solar and wind installations, individual RE projects in India still face substantial financial risks. Addressing these risks and attracting investment, especially from foreign sources, is pivotal for ensuring the successful implementation of renewable energy projects.

Solar and wind projects, expected to drive investment growth, will require 63% of the total investment (240 billion USD). Adding new coal generation capacity will need an additional 76 billion USD by 2032. Amid concerns around availability of private investments for new coal plants, companies in India have recently expressed willingness to the Indian Ministry of Power to either expand existing plants or revive stalled projects.

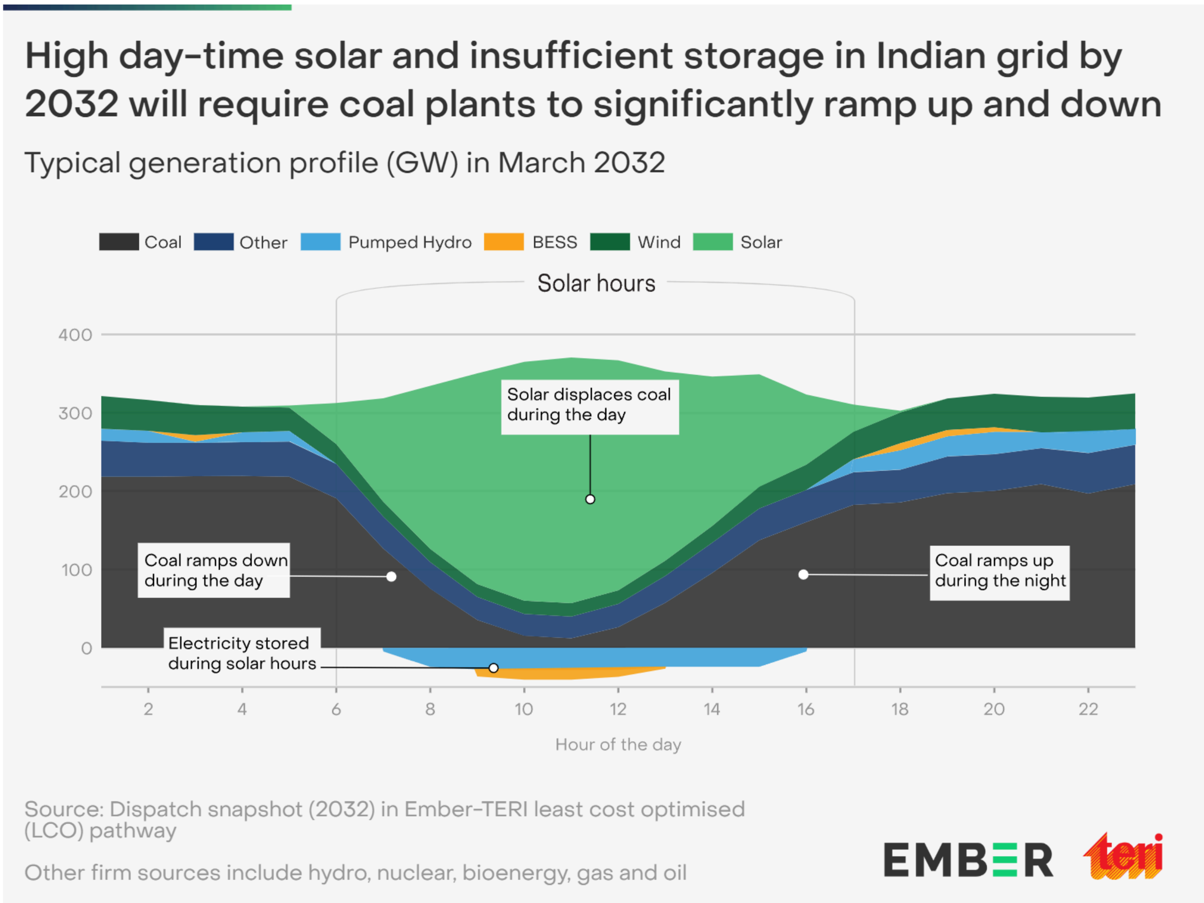
Based on current storage price trends, it is cost-optimal that much of the storage investments will likely go into building pumped hydro storage. However, investments in battery storage are expected to be heavily linked to its cost-effectiveness in the coming decade.



Coal power (in)flexibility & reduced utilisation

For solar growth in the LCO pathway, a significant portion of the coal-based generation capacity must operate in two-shift mode, ramping down or shutting down during solar hours and ramping back up post-midday. The start-ups in daily two-shifting operations could be hot start-ups, which are less damaging or cold start-ups which will entail an increase in operation cost and a cost due to reduced lifetime of the generation capacity. The two-shift operation could entail an increase in cost due to reduced lifetime and a net heat rate increase due to minimum thermal load (MTL).

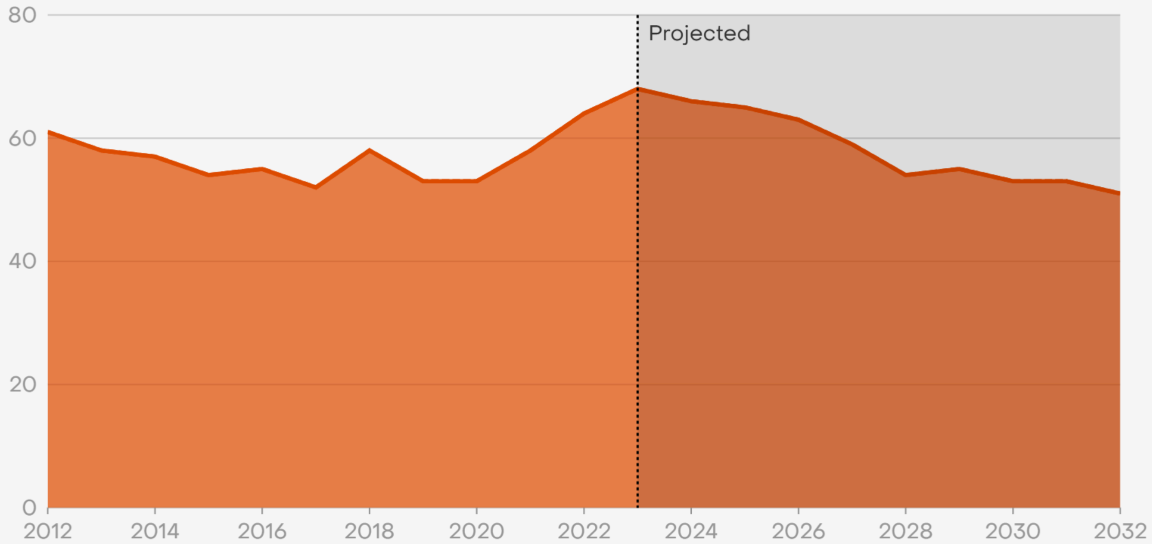
Converting existing baseload coal plants into flexible resources requires examining retrofit costs and operational changes. Research indicates that improving coal plant flexibility could cost between 5%–10% of the total costs of baseload plants. A roadmap for achieving a 40% technical minimum loading for coal capacity involves understanding these costs and necessary modifications for enhanced flexibility.



Under-utilisation of existing coal plants could strain their economics and the power sector overall. This highlights the need to revisit fixed cost recovery mechanisms and evaluate the feasibility and costs of retrofitting coal plants for flexible operation. Our results indicate that coal fleet utilisation is expected to decline from 68% in 2023 to around 50% by 2032 under the LCO pathway.

In the LCO pathway, the utilisation of coal is expected to reduce from 68% in 2023 to 50% by 2032

Plant load factor (PLF) of coal based capacity (%)



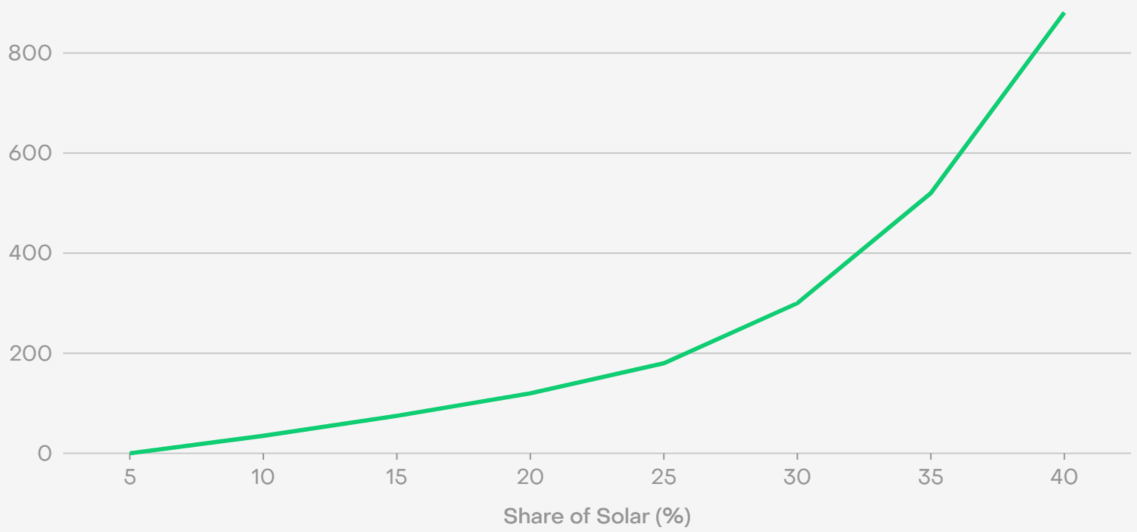
Source: Historical coal utilisation data from India Climate & Energy Dashboard, Projected utilisation as per Ember-TERI least cost optimized (LCO) pathway

Storage requirements with increasing solar

In the LCO pathway, renewable energy (RE) generation growth will account for a significant portion of the total generation growth, especially until the share of solar in the electricity mix reaches 25%. Solar, being the cheapest source of generation during the day, will meet a major portion of the coincidental electricity demand. However, for solar growth beyond 25%, proportional storage must be added to cater to demand during non-solar hours, supporting a higher share of solar energy.

Storage capacity needs to increase significantly once solar share exceeds 25%

Storage capacity required (GWh)



Source: Based on Ember-TERI optimisation model ·
Storage includes Pumped Storage Hydropower (PSH) and Battery Energy Storage System (BESS)

Reducing coal power lock-ins

The LCO pathway in the base case highlights the challenge of coal capacity lock-in, which can limit renewable growth, particularly solar. The "Ladder of Competitiveness" describes how variable renewable energy (VRE) must progress through various stages to replace coal at different points in the phase-down process.

In the base case scenario, while the levelized cost of electricity (LCOE) from solar is lower than from coal, integrating storage with solar is crucial to avoid reaching a saturation point where solar contributes about 25% of total generation. However, solar plus storage is not cost-effective enough to replace new coal capacity until at least 2032, in the base case scenario.

To overcome coal lock-ins, accelerating the reduction in BESS costs becomes essential, as replacing coal with renewable energy plus storage becomes more difficult once new coal plants are operational. Preventing such lock-ins requires faster BESS cost reductions, increased pumped hydro or hydro capacity, expanded wind energy, and better utilisation of existing coal capacity.

Chapter 4 | Key driver to phase-down

BESS project costs need to fall by 15% annually to limit coal capacity addition to NEP level

BESS costs, excluding the cost of finance, need to become about 50% cheaper to avoid adding new coal-based generation capacity.

The rate at which BESS costs decline will significantly influence how quickly renewable energy plus storage (RE+storage) becomes more cost-effective than new coal capacity. For a sustained growth in solar generation, it becomes essential to either shift solar generation to non-solar hours or adjust demand to align with periods of high solar generation. This requirement necessitates the buildup of storage, particularly battery storage, even after demand response measures or increasing daytime demand are considered.

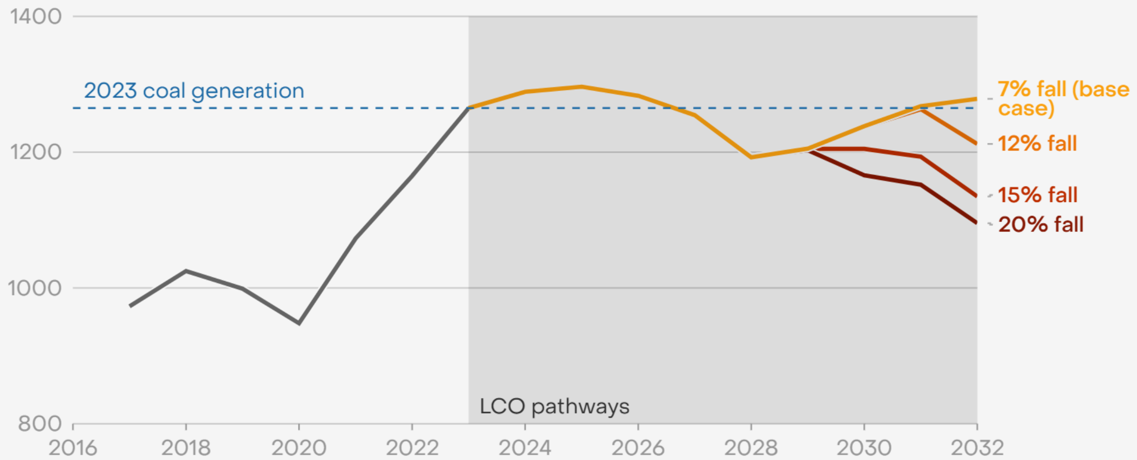
In this chapter, we evaluate how varying declines in capital costs for 2-hour and 4-hour battery energy storage systems (BESS) influence the transition pathway. We explore different scenarios of cost reductions, analysing their impact on generation, storage capacity, and coal reliance. While the base case assumes a 7% annual cost decline, and we investigate scenarios where battery costs decline between 8-20% annually.

We assume 2hr and 4hr storage because a combination of this duration of storage has been deemed necessary till 2030 by multiple studies that examine least cost pathways for India.

We analyse the impact of different battery cost decline rates (7%-20% annually) on generation, storage capacity, and coal capacity buildup and generation compared to the base case scenario, which assumes a 7% annual decline.

Battery project costs need to fall by 7% annually to limit India's coal generation by 2032 to current level

Annual coal generation in LCO pathways for different annual BESS project cost decline scenarios (TWh)



Source: Ember-TERI least cost optimized (LCO) pathway, Ember's India Electricity Data Explorer

BESS (battery energy storage system), LCO for different project cost decline in BESS

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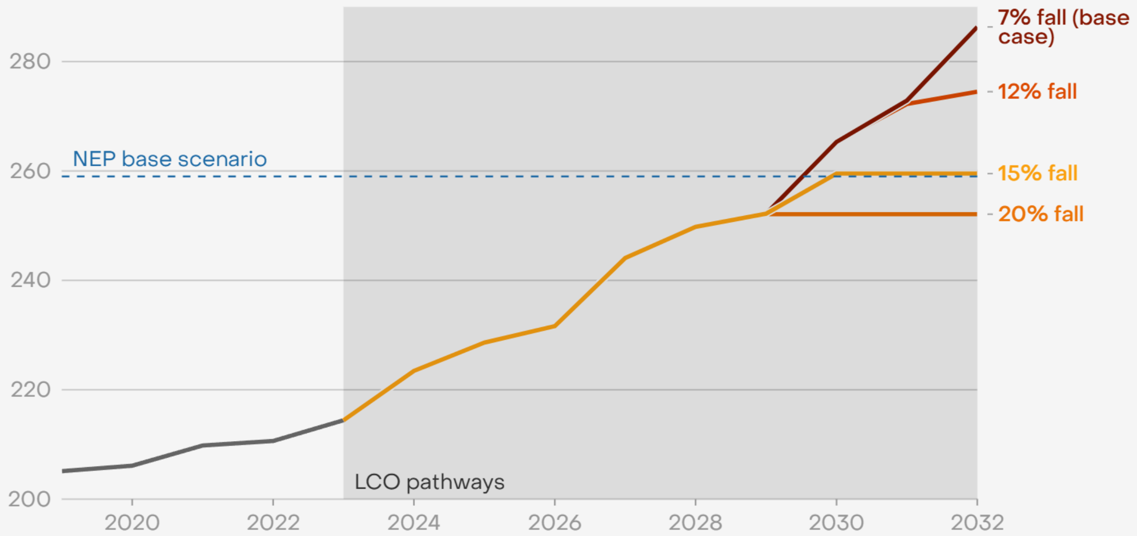
The LCO pathway under the base case scenario, with a 7% annual reduction in BESS costs, will see coal generation starting to plateau, entering stage 2 (see chapter 1) of the coal phase-down. During this stage, the absolute coal generation will hover around the 2023 level of 1,265 TWh to reach 1,280 TWh by 2032. This would represent about 1% increase over the current level. In case BESS costs decline more rapidly, the LCO pathway shifts and coal generation starts declining in absolute terms, reflecting a more accelerated phase-down.

Battery project costs need to fall 15% annually till 2030 to limit coal capacity to NEP14* targets

Coal capacity (GW) in the LCO pathway for different battery cost scenarios



Source: Ember-TERI least cost optimised (LCO) pathway, Ember's Electricity Data Explorer · * 14th National Electricity Plan (NEP14) BESS (battery energy storage system), LCO for different project cost decline in BESS

To limit coal power capacity to the NEP14 projection of approximately 260 GW in the LCO pathway, BESS costs must decline by 15% annually. This would make RE plus storage more competitive against new coal capacity. It is important to note here that even with a 15% annual reduction in BESS costs, the LCO pathway shows an addition of 46 GW of new coal capacity, reaching around 260 GW. The pace of further coal build-up will therefore depend crucially on how quickly BESS costs fall. Limiting it the NEP14 projections will need BESS costs to fall to around Rs 12 Million/MW (or Rs 6 million/MWh). This corresponds to a reduction of over 50% in BESS costs from current levels (~Rs 13 million/ MWh).

The cost of BESS has decreased significantly in recent years. In 2021, standalone storage systems were priced at approximately $450/kWh (Rs 75 million/MW for 2-hour storage). By 2024, this cost had fallen to around $200/kWh (Rs 32 million/MW for 2-hour storage). Co-located storage systems, which integrate storage with generation assets, have seen an even greater reduction to about $150/kWh (Rs 25 million/MW for 2-hour storage), equating to Rs 12.5 million per MWh.

Chapter 5 | Conclusion

Battery storage, building RE fast enough and efficient utilisation of coal capacity are now crucial

The trajectory of coal phase-down and India's overall energy transition in the next decade or so, is critically dependent on how quickly battery storage costs fall, how fast new RE capacity gets built and how optimally existing coal capacity is utilised.

Battery storage costs need to continue to decline and more rapidly

As the share of renewable energy, particularly solar, increases in the grid, effectively integrating these sources while maintaining grid reliability becomes crucial. BESS are essential for this integration, as they store excess renewable energy and provide it during non-solar hours. Facilitating a decline in BESS costs is vital, and policy instruments such as the VGF approved by the Indian Government will play a key role.

It is essential for policymakers to avoid committing to new coal capacity additions without a comprehensive understanding of future battery cost trends. The optimal pathway for the energy transition is highly sensitive to the rate at which BESS costs decline. If battery costs fall faster than anticipated, it could enable a more rapid phase-down of coal, reducing the need for new coal capacity and minimising the risk of underutilised coal plants and higher overall costs. However, this must be balanced with ensuring that there are no peak power shortages. Policymakers will need to navigate this trade-off carefully to achieve a reliable and cost-effective energy transition.

Existing coal capacity needs to be utilised more efficiently

Efforts should focus on optimising the use of existing coal capacity to avoid unnecessary additions of new coal plants. Improved power sharing mechanisms will be essential to manage existing coal capacity effectively. Implementing security-constrained economic dispatch with unit commitment, alongside the phased implementation of Market-Based Economic Dispatch (MBED), will support more efficient and balanced use of coal resources.

Secondly, enhancing the flexibility of the current coal fleet is crucial. This involves retrofitting coal plants to operate efficiently in a two-shift mode, allowing them to ramp down during high solar production periods and ramp up during non-solar hours. Mechanisms to help coal generators recover the additional costs associated with increased net heat rate, higher O&M costs, and reduced plant lifespan due to increased flexibility will be important.

Annual RE build rate needs to be ramped up in the coming years

To achieve the desired energy transition, regular and significant additions of solar, wind, and Pumped hydro storage plants (PSP) are critical. The annual addition targets for these technologies must be met to keep pace with increasing energy demand and renewable energy goals. Continuous monitoring and stock-keeping are essential to ensure that these targets are achieved and to address any challenges that arise.

Supporting Materials

Methodology

Modelling Framework

We use PyPSA to build a co-optimization model for capacity and dispatch to assess the least-cost generation and storage mix at the national level for each year from 2023 to 2032. The model estimates the most optimal (least-cost) mix of capacity to meet demand under specific constraints for each year until 2032. Major constraints include balancing electricity supply and demand, resource supply limits, planning and operating reserve constraints, limits to capacity build-up depending on pipeline and under-construction capacity, construction time, etc.

We assess the optimal resource mix under a range of scenarios. The base case scenario assumptions are described in the following sections, followed by a sensitivity analysis on battery costs to assess the effect on the optimal capacity mix under different capital cost declines for battery storage.

Model Setup: Temporal and Spatial Resolution, Time Horizon, and Optimization Type

- **Time Horizon**: Extending to 2032, with the first year being 2023. The results for 2023 are cross-checked with actual generation shares for different technologies and, to some extent, the build-up of capacity.
- **Optimization Type**: We employ myopic optimization to estimate the year-wise build-up of capacity for generation and storage.
- **Spatial Resolution**: The model does not consider transmission and models a single node for India.
- **Temporal Resolution**:
  - Time slices are selected to incorporate seasonality across the year and inter-day variability of electricity demand and renewable energy generation.

- The capacity build-up for each block is optimised considering the time-varying electricity demand for each year between 2023 to 2032.
- The number of hourly timestamps considered in the investment year is reduced to 2016 hours (84 days, consisting of 7 days from each month) at an hourly resolution to achieve a more manageable simulation run-time. This approach ensures an appropriate representation of seasonal and inter-day variability of electricity demand.
- Each month is represented by a continuous week (Monday–Sunday) that witnessed the peak load for the month.
- The time series load data at an hourly resolution for the aforementioned representative weeks is appropriately stitched together to obtain a continuous load curve for a representative year.

Assumptions

We run scenarios based on the capital cost decline for battery storage, with all other assumptions remaining the same for all scenarios.

Electricity demand

Demand and load curve are assumed to be the same across scenarios. We assume the growth in annual demand and peak demand as shown in the table. The annual demand and peak demand is slightly higher than that assumed in the National Electricity Plan (NEP). This is because we assume a similar growth as per the NEP in future years, but since the demand in 2023 was higher than projected in the NEP, we estimate a higher demand growth in 2023 to match actual annual and peak demand. Demand for different timestamps has not historically been uniform across all time periods.

The hourly load curve for different years was developed using a historical load curve for 2022, assuming growth rates for different individual timestamps.

	Peak Demand (GW)	Total Generation Requirement (TWh)
2024	248	1805
2025	262	1904
2026	277	2013
2027	292	2119
2028	308	2247
2029	322	2351
2030	337	2455
2031	353	2567
2032	370	2693

Electricity supply

On the supply side, we consider a diverse mix of energy sources, including coal, bio power, hydro, nuclear, oil and gas, small-hydro, solar, and wind. This mix represents the current and potential future contributors to India's energy supply landscape, taking into account both conventional and renewable sources.

For storage, we incorporate both pumped storage and battery storage options. Specifically, we consider 4-hour and 2-hour battery storage systems. We assume 2hr and 4hr storage because a combination of this duration of storage has been deemed necessary till 2030 by multiple studies that examine least cost pathways for India

Assumptions around Fixed Cost Projections

Overview of Cost projections assumptions for some years

Rs Million/MW	2024	2027	2032
Coal	85	85	85
Bio Power	50	49	48
Hydro	83	83	83
Nuclear	117	116	116
Oil & Gas	50	50	50
Small-Hydro	80	80	80
Solar	45	45	45
Wind	87	87	87
Pumped Hydro	48	48	48
BESS_2hr	28	22	15
BESS_4hr	51	41	29

Coal

The project cost for coal-based generation capacity was assumed as slightly higher than the Optimal Generation Capacity Mix Study and the National Electricity Plan by the CEA. For our base case scenario, we use a project cost of Rs 85 Million/MW and calculated the annual fixed cost component of existing coal-based capacity using the following financial parameters:

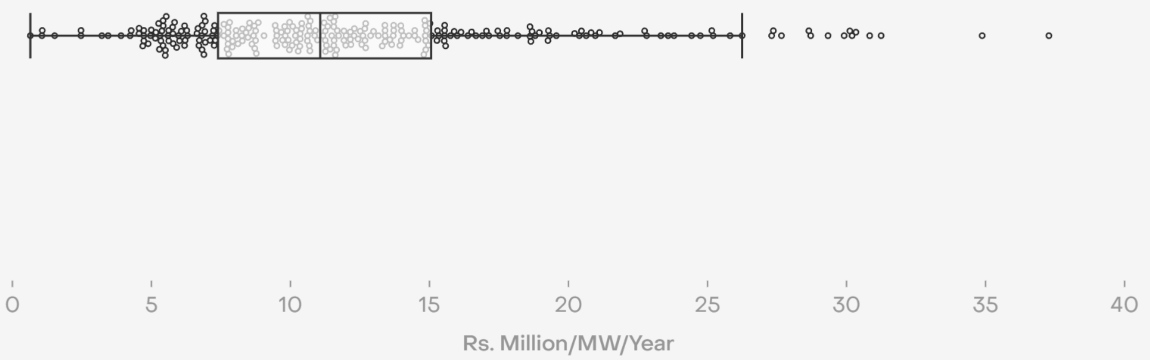
To validate this assumption, we first calculate the annual fixed cost component of existing coal-based capacity using the following financial parameters, which is estimated to be around Rs 12 Million/MW/year.

Financial Parameter	Value
Financial Lifetime	25 Years
Discount Rate	10%
O&M Fixed Cost	Rs 2.66 Million/MW/year

This estimate was cross-checked with the annual fixed cost component for approximately 270 existing coal generators (as shown in the figure), with a median value of Rs 12 Million/MW/year.

Secondly, the corresponding fixed cost in Rs/kWh, assuming an availability factor of 85%, for the assumed project cost, was cross-referenced using data from Merit India and the India Climate & Energy Dashboard (ICED).

Distribution of annual fixed cost liability of existing coal generators in India



Source: Data for 270 existing generators from the climateriskhorizons dashboard

In line with the assumptions used in the Optimal Generation Mix (OGM) study and the National Electricity Plan (NEP), we do not assume any nominal change in project cost.

Bio Power

The capital cost of biomass is assumed to be around Rs 90 Million/MW in the NEP and OGM. However, this appears to be on the higher side considering the cost of electricity derived from biomass, as indicated by the fixed and variable costs in Rs/kWh of existing plants according to ICED. The project cost projections from the First Indian Technology Catalogue for Generation and Storage of Electricity (FITC)—which assumes a capital cost of Rs 50 Million/MW for 2020, with a slight decline to Rs 49.6 Million/MW in 2024 and reaching Rs 47.9 Million/MW in 2032—align better with the actual generation cost of existing biomass generators. Therefore, the capital cost and the fixed O&M cost are assumed as per the FITC.

Large Hydro

For large hydro, we align our assumptions with the FITC projections. The project cost assumptions from the NEP and OGM vary widely, ranging from Rs 60 Million/MW to around Rs 200 Million/MW. This broad range reflects project cost details provided by developers for state and private sector plants and Revised Cost Estimates (RCEs) done periodically by CEA for central sector plants. The variability in costs is likely due to uncertainties around geology and terrain, which impact system design and costs and may not be fully known before a detailed site-level feasibility study. The fixed O&M cost is assumed as per the FITC.

Nuclear

The two types of nuclear power plants being built in India are Pressurized Heavy Water Reactors (PHWR) and Light Water Reactors (LWR). For our analysis, we focus on the optimal build-up of PHWRs only, as most of the new nuclear capacity expected to come online will be PHWRs. This assumption is based on the FITC and verified with the cost of projects under construction and new projects sanctioned in India. The PHWR and LWR capacity in the pipeline is anticipated to be built out according to the expected commissioning dates discussed in subsequent sections. The capital cost for PHWRs is assumed to be in the range of Rs 190-240 Million/MW, with the fixed O&M cost for PHWR-based nuclear capacity aligned with the FITC.

Small Hydro

The International Renewable Energy Agency (IRENA) compilation of historical capital costs indicates that small hydro projects are approximately 30% more expensive than large hydro projects in India. In contrast, FITC projections suggest that small hydro is slightly cheaper (by ~3%) in certain regions due to specific local factors like lower land acquisition costs, regional subsidies, and other incentives that enhance the financial viability and competitiveness of small hydro projects. We back-calculate the average cost of generation from the cost of small hydro, considering both these projections, and compare it with the average cost of generation from existing small hydro capacity (FY 2023). To align the cost of generation with the average cost of generation from existing capacity, we consider a capital cost of 30% higher than the project cost of large hydro.

Solar and Wind

To provide a comprehensive analysis of project costs for solar and wind energy, we utilised historical project cost data from IRENA over the past few years. Additionally, we considered project cost data from the National Electricity Plan (NEP), optimal generation capacity mix

(OGM) study , and the First Indian technology catalogue (FITC). Using a Levelized Cost of Energy (LCOE) model, we estimate the expected tariffs for solar and wind energy projects based on the aforementioned assumptions on project costs. Our assumptions included a discount rate of 10%, capacity utilisation factor (CUF), and a financial life of 25 years.

Using these assumptions, we generated initial tariff estimates for solar and wind energy. We then compared these estimates with trends observed in solar and wind tenders from 2020 to 2023. To ensure that our capital cost estimates were precise and aligned with recent tariff trends, we made adjustments as necessary. For solar energy, we considered the impact of the Approved List of Models and Manufacturers (ALMM) and recent tariff trends, resulting in an assumption of no decrease in solar project costs. Similarly, for wind energy, due to stable tariff trends and the absence of significant decreases in wind tariffs, we did not assume any reduction in wind project costs. Despite projections by multiple sources suggesting potential declines in project costs for both solar and wind energy, we maintained our assumption of stable capital costs.

Pumped Hydro storage

The report by TERI offers a comprehensive analysis of project costs for operational, under-construction, and planned pumped storage project (PSP)capacity in India, highlighting significant variability in cost estimates for different components. According to a study by NREL, the accuracy of pumped storage project (PSP) cost estimates can vary between -50% to +100% across various categories.

For operational PHS capacity in India, the TERI report shows a wide range of cost estimates. For example, the Purulia Pumped Storage Project in West Bengal is estimated to cost approximately Rs 32.8 Million/MW, while the Ghatghar Pumped Storage Project in Maharashtra is estimated at Rs 62.6 Million/MW. The weighted average project cost for operational PHS capacity is around Rs 45 Million/MW.

For new capacity, the TERI reports project costs for several upcoming projects. The Kurukutti Pumped Storage Project (1200 MW), developed by M/S Adani Green Energy, and the Gandhi Sagar Pumped Storage Project (1440 MW), developed by M/s Greenko Energies Pvt. Ltd., are planned for Andhra Pradesh and Madhya Pradesh, respectively. Estimated project costs are approximately Rs 42 Million/MW for the Kurukutti project and Rs 46 Million/MW for the Gandhi Sagar project, resulting in a weighted average cost of around Rs 45 Million/MW. These ranges of values are assumed in our study.

Battery cost

We consider two types of battery storage in our analysis: 2-hour storage and 4-hour storage. For the year 2024, we use the recently discovered capacity tariff for 2-hour battery storage as a reference. To estimate the cost of 4-hour battery storage, we adjust the 2-hour storage costs by accounting for differences in non-battery cost components, based on data from the Lawrence Berkeley National Laboratory (LBNL).

Due to the lack of specific information on battery capacities for ongoing FDRE and RTC tenders, estimating the cost components for each of these project types is challenging. Therefore, we use recent tariffs for standalone battery storage projects for 2024. For instance, Gensol recently won the GUVNL BESS tender with a quoted price of Rs 0.372 Million ($4,452) per MW per month, which is 17% lower than the Rs 0.449 Million ($5,430) per MW per month discovered in GUVNL's standalone battery energy storage auction for 250 MW/500 MWh in March.

To estimate the project costs, we back-calculate using the following assumptions:

- Interest rate: 10% per year
- Operation and Maintenance (O&M) cost: 1% per year
- Project lifetime: 10 years

We calculate the project costs required to achieve a tariff of Rs 0.372 Million ($4,452) per MW per month. For 2024, the assumed project costs are:

- **2-hour storage**: Rs 27.5 Million/MW
- **4-hour storage**: Rs 51.4 Million/MW

Additionally, we explore multiple scenarios for battery project cost declines ranging from 7% (base case) to 25% annually till 2032.

Assumptions on variable costs

The variable costs for each generation technology for new capacity addition can be found in the datasheet.

Overview of Technology Constraints

Limits of Technology Growth

The upper and lower limits of capacity addition, at least for the next 2 years, are based on projects currently in the pipeline, considering their expected year of commissioning. Detailed assumptions regarding these limits, including pipeline capacity for various technologies, can be found in the accompanying datasheet. This approach is particularly relevant for hydro, nuclear, and pumped storage projects, which typically have longer gestation periods.

Additionally, we impose limits on the annual growth rates for solar and wind capacity to ensure that our projections remain realistic and aligned with market dynamics. We restrict annual growth in solar and wind capacity by 35% year on year, up to a maximum of 64 GW of solar by 2030 and 12 GW of wind by 2030. For further details, please refer to the datasheet for the assumptions used.

Broad Technology Constraints

Details around the operational constraints are provided in the assumption sheet. Key operational constraints are summarised below:

- **Solar Energy**: We assume a Capacity Utilisation Factor (CUF) of 22-24%, reflecting a modest improvement from the base year of 2023 to 2032 due to advancements in technology and increased efficiency in solar panels.
- **Wind Energy**: We anticipate a Capacity Utilisation Factor (CUF)of approximately 35% for new wind plants, accounting for site-specific conditions and the growing maturity of the sector.
- **Large Hydro**: We estimate an annual CUF of around 41%, based on actual generation data from recent years. We limit the dispatchability of large hydro to 30% of the total generation, with the remaining dispatch following the hourly generation profile of existing hydro projects.
- **Pumped Hydro Storage**: We estimate an annual CUF of around 41%, based on actual generation data from recent years, as it plays a crucial role in balancing intermittent renewable generation.
- **Battery Storage**: Projected round-trip efficiency is about 88% for batteries and 75% for pumped hydro storage, representing the proportion of energy retrievable compared to the energy input, accounting for losses during charging and discharging.

- **Coal-Based Capacity**: We assume a maximum generation capability of 82% (at any instant) of its rated capacity, based on historical performance data, which includes considerations for availability, auxiliary power consumption, and constraints related to the sale of excess generation. Other assumptions such as minimum generation level, ramp rates, etc can be found in the datasheet

For comprehensive details on these constraints and assumptions, please refer to the datasheet.

Existing generation and capacity data

Existing generation and capacity data are taken from Ember's India Electricity Data Explorer. The underlying data is mainly sourced from the Central Electricity Authority, see methodology. This is in-line with India's National Energy Plan, but excludes some amount of captive generation.

Existing penetration of renewables is calculated from Merit data.

Existing generator data

Data on existing generators including capacity, fixed cost liability and variable cost was collected and verified through multiple sources including the India climate and energy dashboard, Merit India, climate risk horizons dashboard and IECC.

Acknowledgements

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Header image

Aerial of the Kogan Creek Power Station energy hub with a big battery (BESS) solar and wind generation assets.

Credit: **Lincoln Fowler / Alamy Stock Photo**