Budgeting for Net Zero: Powering India's reliable clean energy future

An assessment of firm and dispatchable renewable energy (FDRE) competitiveness to 2050

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Executive Summary

India's electricity demand is increasing rapidly in response to economic development, expanding energy access, urbanization, digitization, and climate-induced heat stress. Whether this demand is met from renewable energy or fossil fuels has major implications for energy costs, air pollution, industrial development, and India's net-zero ambitions. Coal continues to be the mainstay of India's electricity generation, with 80 GW of new thermal power plants planned to 2032. But cost declines in renewable energy and batteries are changing the value proposition, opening new pathways to achieve India's energy security needs.

In 2023, the Government of India introduced a new tender design for utility-scale firm and dispatchable renewable energy (FDRE): hybrid solar, wind, and energy storage installations that can deliver electricity in a predictable manner aligned with the demand profiles specified by electricity distribution companies (discoms). FDRE tenders are India's renewable energy solution to providing round-the-clock power supply from variable renewable energy in an electricity market dominated by long-term power purchase agreements. However, it has so far been only a partial success, with 9.7 GW under construction, 4.2 GW of tenders cancelled, and ~8 GW not awarded.

Several factors have affected this slow market uptake. For developers, there is uncertainty about the ideal blend of variable renewable energy and storage to deliver contractual obligations. In addition, FDRE requires developers to install some additional capacity or storage to compensate for variability and ensure firm delivery, leaving developers with surplus power. Uncertainty about how to monetize this generation is a key risk. For discoms, there is a risk that penalties for non-fulfillment of firm delivery might be insufficient to deter non-compliance, undermining confidence in "firmness." When comparing costs, discoms sometimes benchmark FDRE against plain solar or wind rather than against other sources of firm power, obscuring FDRE's true value.

This study investigates the circumstances under which FDRE is cost competitive with new coal-fired thermal power plants, the size and nature of government support needed (if any) to accelerate FDRE deployment, and the macroeconomic impacts of scaling up FDRE. A key variable is how much of the surplus power in FDRE developments can be sold in the market for additional revenue.

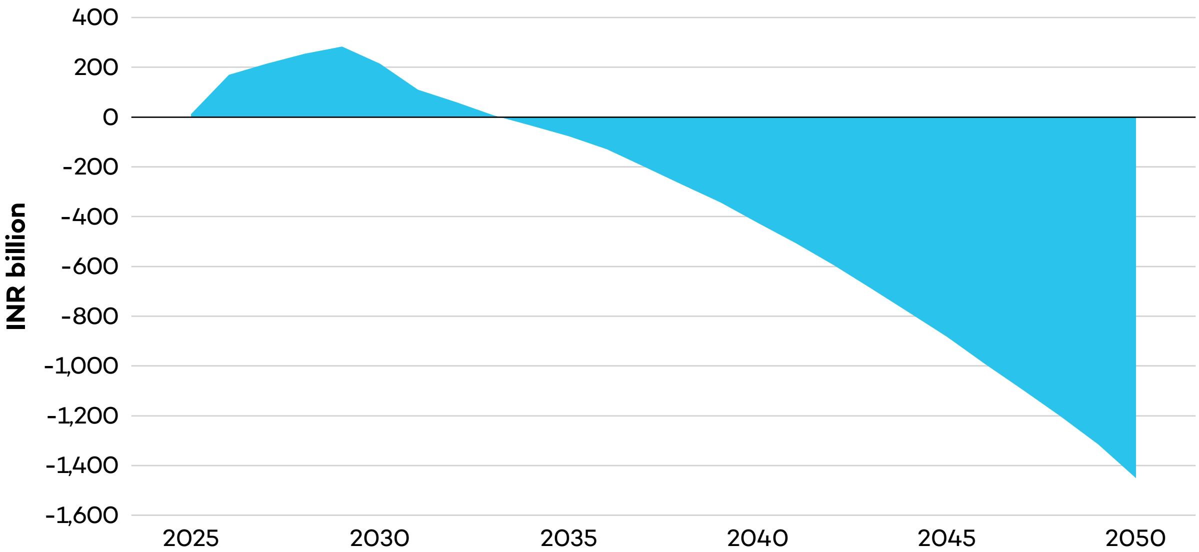
We projected that FDRE is competitive with coal

- from 2025 when 100% of surplus power is sold ("100% surplus sold"),
- from 2030 when 50% of the surplus power is sold ("50% surplus sold"), and
- from 2047 when 30% of the surplus power is sold ("30% surplus sold").

These projections are based on the effective levelized costs of FDRE in India, factoring in learning rates that account for cost declines in solar, wind and battery storage. The coal benchmark tariff was for a new pithead coal plant, the most common source of new thermal power in India (INR 4.65 per kWh). We conservatively assumed that FDRE makes up around 15% of total solar and wind deployment to 2050. The sale of surplus electricity from FDRE developments was assumed to be at average market prices for the open energy market (INR 5.62/kWh).

In our consultations, developers did not reveal specific strategies underlying their tenders due to commercial confidentiality and rising competition. Consultations with experts indicate that developers may be using a mix of strategies to sell surplus power and boost non-contractual revenues. Real-world tender prices are similar to our bottom-up estimates, based on the levelized costs for FDRE and the sale of 30% to 100% of surplus power at average market prices. Developers appear to be optimizing their earnings based on revenue from the sale of surplus power and accepting penalties resulting from failure to meet the committed generation. Our scenarios model these different revenue optimization strategies and estimate the cost gaps.

Figure ES1. Cumulative cost gap estimation for FDRE (compared to coal) between fiscal year (FY) 2025 and FY 2050 for the 50% surplus-sold scenario

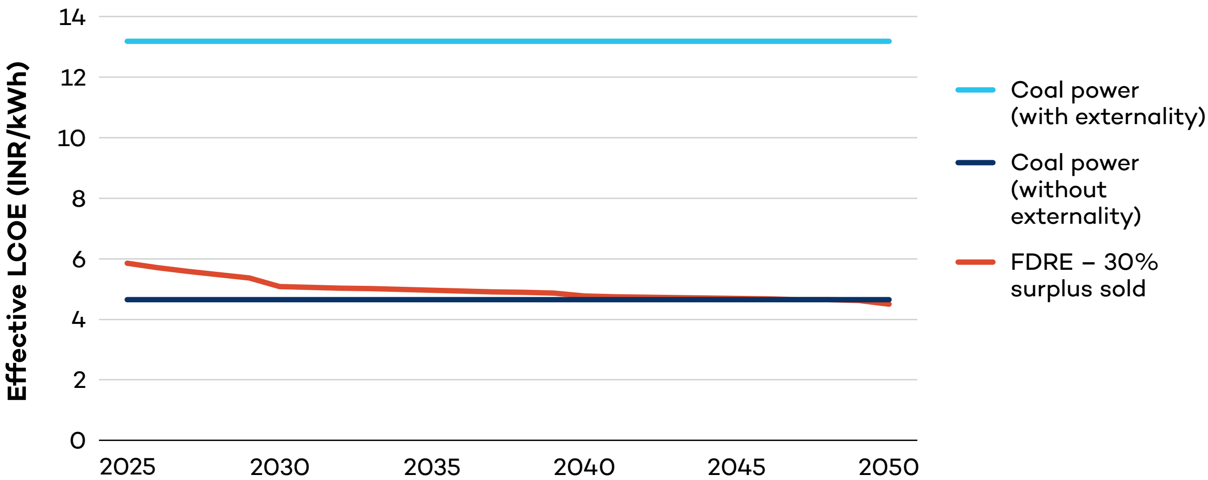


The scenario with 100% surplus-sold resulted in energy cost savings (relative to the coal benchmark) from the first year of implementation, with cumulative savings reaching INR 4,060 billion (USD 47.7 billion) by 2050. In the 50% surplus-sold scenario, the cost gap to 2030 (when cost parity was achieved) was INR 284 billion (USD 3.3 billion) and the savings from then to 2050 were INR 1,735 billion (USD 20 billion). In the 30% surplus-sold scenario, there is a cost gap between the benchmark coal price and the effective FDRE levelized cost of electricity (LCOE) until 2048 (totalling INR 1,636 billion/USD 19.2 billion) when cost parity with coal is reached and net savings are seen thereafter.

Where a cost gap is predicted to exist, it could be bridged in several ways. First, public financial support could be provided to FDRE developers. However, this is unlikely to be necessary given that existing tenders have not required dedicated subsidy programs. An alternative approach is to redesign FDRE tenders to provide more flexibility (i.e., reduced demand fulfillment ratios that reduce the need for oversizing) or to include a capacity charge for battery storage that can provide system-wide services (such as ancillary services). This would align developer incentives with national resource adequacy goals and strengthen both grid reliability and market efficiency as India's power system evolves. In addition, non-fiscal government supports could be provided to developers, such as ensuring access to land or transmission.

Evaluating FDRE and coal-based power purely on energy costs is not a fair comparison. Both coal generation and FDRE can provide reliable power, with the storage element of FDRE also potentially providing balancing and inertia. However, coal combustion also results in costs on society that are not reflected in its energy price. We estimated the unit costs of three key externalities of coal combustion: morbidity and mortality caused by air pollution, and climate change. Adding these costs to the coal benchmark increased its effective LCOE in 2025 to INR 13.19/kWh (USD 0.15/kWh), making FDRE immediately competitive in all scenarios (Figure ES2). Further, coal-fired power plants in India typically face commissioning timelines of 5–7 years, compared to 2–2.5 years for FDRE projects, highlighting FDRE's structural advantage in faster, modular deployment and lower exposure to cost and regulatory delays.

Figure ES2. Cost-competitiveness of FDRE and coal power after accounting for the costs of externalities



From a macroeconomic perspective, FDRE results in higher economic growth and net job creation than our baseline scenario (no FDRE). On an annual basis, FDRE would result in GDP being 0.5% higher in 2032, 1% higher by 2038, and 1.8% higher by 2050. Net additional job creation from FDRE reaches 64,000 jobs in 2050 (after adjusting for reduced employment in coal power plants).

FDRE also contributes to a reduction in greenhouse gas emissions and air pollutants, generating net societal value even in the 30% surplus-sold scenario. Therefore, there are two dividends from FDRE: one is the energy cost reduction when FDRE is adopted (after cost parity is reached), and the second is additional economic growth resulting from higher labour productivity due to a reduction in health and climate costs.

Examining FDRE against the key criteria of energy security—availability, affordability, accessibility, and acceptability—demonstrates clear benefits across all aspects. FDRE can provide round-the-clock power, costs are falling, it is faster to build than new coal, once built, it is not dependent on imported or price-volatile commodities, and it has lower externalities. FDRE demonstrates that renewables and storage are a viable alternative to coal and gas.

However, the model has pros and cons, like all energy solutions. The need to oversize capacity is inefficient and may not necessarily lead to lowering system-wide costs if the surplus capacity is monetized by higher price spreads. The surplus energy at peak times, such as midday solar, may have limited monetization options, increasing risks and financial burdens on developers. FDRE tenders could strain land use, resource allocation, and transmission infrastructure, yet deliver only contractual minimums in terms of dispatchable power.

Governments should therefore discern and promote the most appropriate type of clean energy based on system needs. FDRE can be prioritized where energy is needed to fit a specific demand profile (the demand fulfillment ratio [DFR]) and peak needs. Elsewhere, strong emphasis should be on procuring standard solar and wind projects (hybrid) together with strategically sited stand-alone energy storage systems to deliver system flexibility and firming services more cost-effectively than integrated FDRE projects.

Stand-alone storage can be sized independently and deployed at locations that maximize value (congestion relief, local reliability, peak shaving), enabling

1. more efficient utilization of capital—storage can be sized exactly for the required firming rather than oversized to meet burdensome DFR targets;
2. better system integration and dispatch flexibility, as storage can respond to grid needs dynamically; and
3. multiple revenue streams—capacity, energy arbitrage, ancillary services—particularly as markets mature.

The Government of India can consider several policy measures to support clean energy technologies that would benefit FDRE:

1. Continue to develop and deepen the wholesale electricity market to enable energy storage projects and access multiple revenue streams. This will ensure that the lowest-cost variable renewable energy and storage can be effectively integrated into the grid, supporting efficient levels of oversizing required for FDRE projects and minimizing idle capacity in the system.
2. Better enforcement of Renewable Purchase Obligations and Renewable Consumption Obligations, as envisaged in the Electricity Act, 2003, to further incentivize discoms to sign supply agreements.
3. Enforce air pollution controls on coal-fired power plants based on the polluter-pays principle or impose a carbon price on coal to reflect its societal costs. Alternatively, include socio-economic metrics in clean energy tender prices to provide a price premium to reflect reduced pollution compared to coal power.
4. Continue support for battery energy storage systems (BESS) through viability gap funding or by providing manufacturing incentives for promoting domestic manufacturing to drive down the costs of locally sourced panels.

Where FDRE is considered the most appropriate option, several policy options could maximize tender uptake:

1. Undertake confidential negotiations with discoms and developers on the barriers to accelerating FDRE uptake and the redesign of FDRE tenders, such as:
    - less onerous DFR requirements to reduce the amount of oversizing
    - a capacity charge for battery storage that can provide system-wide services (such as ancillary services)
    - ensure penalties are sufficient to ensure firmness of agreed DFRs to give procurers confidence in FDRE as a reliable source of power—for example, through penalty calibration linked to transparent benchmarks, complementary mechanisms such as insurance-like instruments that share risk more efficiently, or clear safeguards against retrospective changes.
2. Shift to other support mechanisms for FDRE based on market prices, such as contracts for difference or a capacity investment scheme.
3. Provide clear guidance to discoms on methodologies to compute short-term, medium-term, and long-term resource adequacy and incentivize integrated resource planning at the state level through capacity-building initiatives
4. Create guidelines for technology-neutral capacity auctions where FDRE can compete directly against coal and other firm sources, based on objective metrics such as minimum availability, ramp rate, and ability to provide ancillary services.

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Abbreviations and Acronyms

BESS	battery energy storage system
C&I	commercial and industrial
CapEx	capital expenditure
CO_2	carbon dioxide
CEA	Central Electricity Authority
DEA	Danish Energy Agency
CERC	Central Electricity Regulatory Commission
CfD	Contracts for Difference
CIS	Capacity Investment Scheme
CUF	capacity utilization factor
DAM	day-ahead market
DCR	Domestic Content Requirement
DFR	demand fulfillment ratio
discom	distribution company
ESS	energy storage systems
FDRE	firm and dispatchable renewable energy
FGD	flue gas desulphurization
FY	fiscal year
GEM	Green Economy Model
GHG	greenhouse gas
ICRA	Investment Information and Credit Rating Agency
IESO	Independent Electricity System Operator
ISTS	Inter-State Transmission System
LCOE	levelized cost of electricity
MNRE	Ministry of New & Renewable Energy
MoP	Ministry of Power
NHPC	National Hydroelectric Power Corporation
NTPC	National Thermal Power Corporation
O&M	operations and maintenance

PHS	pumped hydro storage
PJM	Pennsylvania-New Jersey-Maryland
PLI	Production Linked Incentive
$PM_{2.5}$	particulate matter (measuring less than 2.5 micrometres in diameter)
PPA	power purchase agreement
PV	photovoltaic
RCO	Renewable Consumption Obligation
RfP	Request for Proposal
RfS	Request for Selection
RPO	Renewable Purchase Obligation
RTC	round-the-clock
SCC	social cost of carbon
SEBI	Securities and Exchange Board of India
SECI	Solar Energy Corporation of India
SJVN	Satluj Jal Vidyut Nigam
TPP	thermal power plants
VGF	Viability Gap Funding
VOLL	value of lost load
VSL	value of a statistical life

1.0 Introduction

Over the next 3 years (2025–2027), India's electricity demand is projected to grow by 6% annually (Çam et al., 2025). Renewable energy capacity has rapidly expanded as a low-cost, clean energy solution to meet the rising electricity demand. This expansion also helped India achieve one of its nationally determined contribution targets 5 years ahead of time: 50% of India's cumulative installed capacity is now from non-fossil sources (as of July 2025). The growth has mostly been in solar and wind, variable renewable energy (VRE) that requires storage to dispatch power to meet demand at all hours (International Energy Agency, 2025).

The Government of India introduced firm and dispatchable renewable energy (FDRE): hybrid energy systems (solar, wind, and energy storage) that can deliver clean electricity in a predictable manner and is aligned with the demand profiles specified by electricity distribution companies (discoms) (Jacob, 2024). India is also adding sizable coal-fired capacity, nearly 80 GW by 2032, to (i) meet growing demand, (ii) ensure round-the-clock (RTC) power, and (iii) maintain affordability (Palit & Khurana, 2025; Press Information Bureau, 2024b). This need for new coal-fired capacity is increasingly contested: the need for firmed power can be met through accelerated low-cost clean energy deployment and smarter demand management; reliability can be addressed with storage and flexible renewables; and new coal plants risk becoming stranded assets while contributing to air pollution and greenhouse gas (GHG) emissions. Continued reliance on coal could also exacerbate the financial stress of discoms, locking them into long-term power purchase agreements (PPAs) that oblige them to pay high fixed charges even when plants are underutilized. FDRE is projected to become cheaper over time, reducing demand for coal and leaving discoms burdened with underutilized coal plants.

FDRE represents a paradigm shift from generation-based renewable energy systems to demand-based clean power solutions. It offers a pathway to displace coal by delivering renewable energy that is reliable and dispatchable while catalyzing domestic industries in battery, solar photovoltaic (PV) and wind manufacturing, system integration, and grid services.

This study aims to guide decision making and design of government support for FDRE through cost analysis and scenario construction. We address the following questions:

1. What is the difference in levelized costs between FDRE projects and new thermal power plants (TPPs) in India (the "cost gap")?
2. How much and what kind of government support is needed, if any, to make FDRE viable for discoms and developers/investors?
3. How will support for FDRE impact the broader energy ecosystem, economy, society, and environment?

The study is the second in a series to investigate whether India's public financial support mechanisms are sufficient to achieve its clean energy ambitions. Our previous study estimated the support needs for a range of clean energy technologies (Raizada et al., 2024). The work focuses on India but has important lessons for other economies looking to decarbonize through green growth.

2.0 Context

India has developed a range of government tender models to procure renewable energy that is firm and dispatchable. "Firm" refers to the ability to deliver contracted power across committed hours, while "dispatchable" refers to the system's ability to respond dynamically to demand when needed. FDRE refers to a type of government tender for utility-scale renewable energy that combines (Ministry of Power [MoP], 2023b)

- solar PV and onshore wind plants, as these systems have complementary generation profiles, and
- energy storage systems (ESSs) for increasing the reliability and dispatchability of renewable energy. While several energy storage systems exist, in this study, we consider only lithium-ion battery ESSs (BESSs).

The FDRE model reflects India's shift from generation-centric to demand-centric renewable procurement, aiming to integrate more renewable energy while maintaining grid stability. By requiring developers to manage renewable energy variability, the government transfers operational and financial risk away from grid operators and utilities (Box 1). Four broad configurations exist under this framework, based on their dispatchability capabilities and availability requirements:

1. **Assured peak**: Guarantees renewable power supply during pre-defined peak demand windows, such as morning and evening peak hours. The procurer predetermines and communicates to the generator to deliver power at a 90%–95% metric of contracted capacity either during the tendering/contracting stage or during operations (Figure 1 and Figure 2).
2. **Load following**: The renewable energy supply would need to be ramped up or down dynamically to match the buyer's real-time demand profile at an operational availability range of 75%–90%.
3. **RTC**: The developer is mandated to supply consistent daily power across all hours of the day. This includes maintaining peak capacity at a specified percentage or at a pre-determined profile
4. **Peak-only**: The generator is mandated to deliver reliable power exclusively during a designated peak period, as predefined and communicated by the procurer. The obligation is limited to those hours, and there is no requirement to supply power outside the peak window.

While each of these models is designed to ensure that generation from renewable energy sources is firm and dispatchable, the final choice of model may depend on the demand profile, resource complementarity, cost considerations, and policy or regulatory requirements. Notably, in FDRE tenders, energy storage is primarily used for demand shifting to meet contractual firmness and dispatch obligations. While energy storage technologies such as batteries are technically capable of providing other services, such as frequency regulation, ancillary support, or backup supply, these functions are not explicitly required or remunerated under current FDRE tender guidelines. The integration of such services remains subject to evolving provisions for inverter-based resources (like solar, wind, and BESS) under the Indian Electricity Grid Code 2023, India's key system operation regulation (Central Electricity Regulatory Commission [CERC], 2023).

Box 1. Why is India experimenting with FDRE tenders?

FDRE projects are an interim procurement mechanism to ensure reliable, time-bound renewable energy supply while India's electricity market transitions toward more market-based flexibility instruments. India's electricity market remains dominated by long-term PPAs for new capacity additions, while short-term power markets accounted for around 12.5% of the total generation in 2023/2024, including exchanges, bilateral, and deviation settlement mechanism transactions (CERC, 2024).

India's ancillary services market remains nascent. There is no dedicated primary reserve market, and although the CERC Ancillary Services Regulations (2022) now enable market-based procurement of secondary and tertiary reserves, most services are still secured through operator-directed (shortfall or emergency) dispatch from thermal and hydro units rather than market clearing (CERC, 2022, 2024).

India also lacks a capacity market, and therefore all renewable energy generation earns revenue for energy delivered. In June 2023, the MoP published its *Guidelines for Resource Adequacy Planning Framework for India* and subsequently released the *Draft Discussion Paper on Methodology for Capacity Credit of Generation Resources*, which lays down the principles to assist states in bottom-up resource adequacy planning; however, most states are yet to start this process (MoP, 2023a, 2024b).

In the absence of capacity markets and the lack of grid flexibility, the Grid Controller of India has a limited set of tools to manage the variability associated with renewable energy. Primary and spinning reserves are technically maintained by coal and hydro plants but have limited ramping ability, making centralized balancing less responsive. Further, many discoms still struggle to forecast demand accurately (due to weather, agriculture load, rooftop solar, electric vehicles, etc.) and have weak forecasting tools, making it even harder for the system operator to make the grid demand responsive in real time.

Contrary to this, mature power systems in the United States, Great Britain, and Australia rely on integrated capacity and ancillary markets where system operators procure reserves and balancing resources through transparent auctions. System operators play a central role in maintaining system reliability by forecasting peak demand and procuring balancing resources. Deviations between forecasted and actual supply or demand are managed in real time via these markets.

With such instruments still developing in India, FDRE tenders effectively internalize balancing costs, shifting the responsibility for firmness and dispatchability from the system operator to the project developer. FDRE tenders also allow discoms to procure firm capacity competitively via Section 63 of the Electricity Act, 2003 in the absence of system-wide capacity auctions. Developers bundle renewable generation with storage (or flexible capacity) under a single tariff, offering discoms predictable, contractually firm supply.

However, current FDRE designs primarily ensure discom-level reliability, not system-wide flexibility. Storage embedded in FDRE projects is usually dedicated to meeting contractual schedules, leaving little capacity for participation in ancillary markets. Over time, as India's power system evolves, FDREs could be redesigned to reserve a share of flexible capacity for system-wide services, aligning developer incentives with national resource adequacy goals and strengthening both grid reliability and market efficiency.

2.1 Early Experiments Before FDRE in India (2019—2023)

India's FDRE framework builds on earlier experiments, including versions of RTC and assured peak tenders, incorporating their lessons into a more comprehensive design. This evolution culminated in the MoP's 2023 FDRE guidelines, which established a robust, storage-backed framework for delivering renewable power in line with specified demand profiles.

In October 2019, the Solar Energy Corporation of India (SECI) issued India's first RTC tender (RTC-1) for 400 MW of RTC power. Developers could combine solar, wind, hybrid, and thermal configurations with optional storage to meet a minimum monthly and annual capacity utilization factor (CUF) requirement of at least 80% and a monthly CUF of at least 70% (Takkar, 2020). This obligation was tied to a 25-year PPA with annual tariff escalation up to 3% per year for 15 years (Bridge to India, 2020).

Prayas Energy Group's analysis of the awarded 400 MW capacity showed that the CUF targets were technically achievable, even without storage. However, this was possible only by substantially oversizing renewable energy capacity, which in turn would have led to large volumes of surplus generation[1] that were difficult to monetize (Gambhir et al., 2020). This made flexible backup or storage the more practical solution for consistent performance. However, the high cost of batteries at the time could have reduced margins when combined with BESS.

In March 2020, the SECI issued an ambitious 5,000 MW RTC-2 tender combining renewables with thermal backup (Thomas, 2020). The tender was amended seven times, reducing the capacity to 2,500 MW. The SECI also revised the performance metrics to require 85% annual availability, with stricter penalties for shortfalls (Garg et al., 2021). Crucially, it stipulated that at least 51% of the annual energy supply must come from renewable energy (including stored energy derived from renewable energy), with the balance allowed from thermal power (SECI, 2020). After a span of two and a half years since the release of RTC-2, SECI issued the RTC-3 tender with 2,250 MW capacity in September 2022 (Takyar, 2022). The tender was eventually cancelled due to a lack of bidder interest resulting in fewer auction numbers (Shetty, 2023).

SECI continued procurement under the RTC banner and released its RTC-3 tender in September 2022 (aggregate capacity of 2,250 MW), which allowed developers to complement renewables with thermal power as backup, rather than relying solely on storage or oversizing

[1] ReNew, who won the tender at INR 2.9/kWh first year tariff, is building 900 MW solar and 1,300 MW wind along with 100 MWh BESS to cater to the requirement.

of renewable energy capacity (Takyar, 2022). Simultaneously, SECI also experimented with various other types of hybrid tenders (e.g., solar-wind hybrids, assured peak supply), testing flexible models alongside the formal RTC rounds (Goyal, 2022).

2.2 The Shift Toward Storage

While RTC offered a more reliable alternative to stand-alone renewables, its design between 2019 and 2023 was strongly shaped by cost considerations. During this period, storage costs remained high, which made it difficult to ensure affordable tariffs if battery storage was mandated. To enable competitive price discovery and make RTC power attractive for buyers, tenders kept battery storage optional and allowed developers to incorporate thermal backup to meet the CUF requirements. In practice, this approach helped control tariffs but also meant that many projects relied on thermal backup rather than storage.

Over time, however, the steady decline in battery storage costs began to shift the cost economics. Battery prices fell from INR 79 lakh/MWh in 2015 to INR 17 lakh/MWh in 2025, marking a significant decrease of 80% over the decade. This paved the way for the integration of batteries directly into renewable energy-based procurement models (Investment Information and Credit Rating Agency [ICRA], 2024b). These cost trends, combined with RTC lessons, informed the MoP's next step: the 2023 FDRE guidelines.

Box 2. Demand fulfilment ratio

The DFR is a key performance metric used in FDRE tenders to evaluate whether the contracted renewable supply is meeting the agreed delivery profile. It is calculated by dividing "actual energy delivered to the buyer during the specified hours" (numerator) by "energy committed in the contract for those hours" (denominator). A higher DFR signals greater reliability and dispatchability. The DFR is thus used as a proxy parameter to evaluate the dispatchability of load-following FDRE tenders. In contrast, alternative configurations, such as RTC, prescribe monthly or annual CUF and hourly dispatchability requirements in cases of assured peak power tenders.[2] While CUF measures how much of a plant's capacity is utilized over time, DFR measures how much of the offtaker's requested demand is met by that supply.

Falling short of the DFR threshold can trigger penalties or payment reductions, commonly 1.5 times the tariff for the energy not supplied. However, the adequacy of this penalty level in ensuring reliability without undermining project viability remains debated. Box 3 explores this trade-off in detail, examining whether the current 1.5 times penalty provides sufficient incentive for developers to maintain firmness while keeping bids competitive.

[2] CUF assesses the utilization of power generation plants. It represents the ratio of the actual energy generated by a plant to the maximum possible energy it could have generated over a specific period.

Box 3. Balancing firmness with viability: Penalties and incentives for FDRE

The question of an appropriate penalty structure for FDRE remains one of the most nuanced and contested aspects of market design. While the commonly applied penalty set at 1.5 times the contracted tariff constitutes a significant premium and is designed to incentivize developers to meet their obligations through oversizing or storage, it must be assessed in the broader context of India's economic valuation of unserved energy.

Recent estimates by Khanna and Rowe (2024) place India's value of lost load (VOLL) at INR 124.22/kWh (Khanna & Rowe, 2024), broadly consistent with the INR 140/kWh illustrated in the *Guidelines for Resource Adequacy Planning Framework for India* (MoP, 2023a). These figures reflect the very high social and economic costs of electricity outages. By contrast, the market ceiling price is only ~INR 10/kWh (Goswami, 2023), well below the cost of alternative back-up such as diesel generation (typically INR 25–40/kWh) (Power Line Magazine, 2024). Against this benchmark, a 1.5× penalty (~INR 7.5/kWh if the contracted FDRE tariff is INR 5/kWh) appears modest. It may signal financial risk to developers but falls far short of the true economic cost of lost load, raising legitimate concerns for discoms and regulators about whether current penalty levels provide sufficient assurance of firmness.

At the same time, penalties that are set at a very high level risk distorting the market in the opposite direction. Developers may be forced to design projects around extreme stress scenarios that drive up costs, leading to either unviable bids or higher procurement prices. This can hinder broader participation, limit innovation in contract design, and make FDRE more expensive than intended. For a developing market like India's, preserving sufficient space for competitive entry remains important alongside ensuring reliability.

The trade-off is clear: too low, and FDRE is perceived as "infirm" by the discoms; too high, and FDRE risks becoming prohibitively expensive. A balanced approach is therefore to view penalties not as a stand-alone lever, but as part of a broader contract architecture. This architecture could combine:

- **Penalty calibration linked to transparent benchmarks** (e.g., day-ahead market [DAM]/real-time market averages, or a fraction of diesel costs): These market-based benchmarks also naturally reflect seasonal variation, such as higher prices (and higher VOLL) during peak summer months compared to monsoon or winter, making the penalty framework more responsive to real system conditions.
- **Complementary mechanisms, such as insurance-like instruments that share risk more efficiently**: Instead of penalties falling entirely on developers, part of the variability risk could be pooled or hedged through market-based insurance mechanisms. This would give procurers reliability assurance without forcing developers to over-engineer capacity for rare extreme events. Even with higher penalties, such mechanisms could preserve bidding incentives and project viability, as they distribute risk across multiple projects while keeping the costs manageable.

- **Clear safeguards against retrospective changes**: While penalties may evolve over time, they should apply only prospectively. Retroactive revisions to past contracts or charges undermine predictability and can erode investor confidence.

Over time, as India develops better empirical estimates of reliability costs through resource adequacy studies, penalties could evolve toward a more formal link with VOLL. Until then, the priority should be to maintain a transparent and balanced penalty design that is strong enough to give procurers confidence in firmness, but flexible enough to keep bids viable and participation broad. Only then will FDRE be trusted as both a credible and scalable part of India's power mix.

Under the FDRE framework, procurers can choose among multiple configurations of solar, wind, and ESSs to supply demand-following, peak power supply, or RTC supply, as defined in each Request for Selection (RfS). Specific performance requirements and penalties were not set in the guidelines, as they were supposed to be determined in each individual RfS. For example, SECI's FDRE tenders have commonly required a monthly demand fulfillment ratio (DFR) of 75%–90% and linked shortfalls to penalties (Box 2) (SECI, 2023). This tender-specific approach lets buyers tailor firmness and costs to their needs while operating within the national FDRE framework (Rodrigues, & Vembadi, 2024).

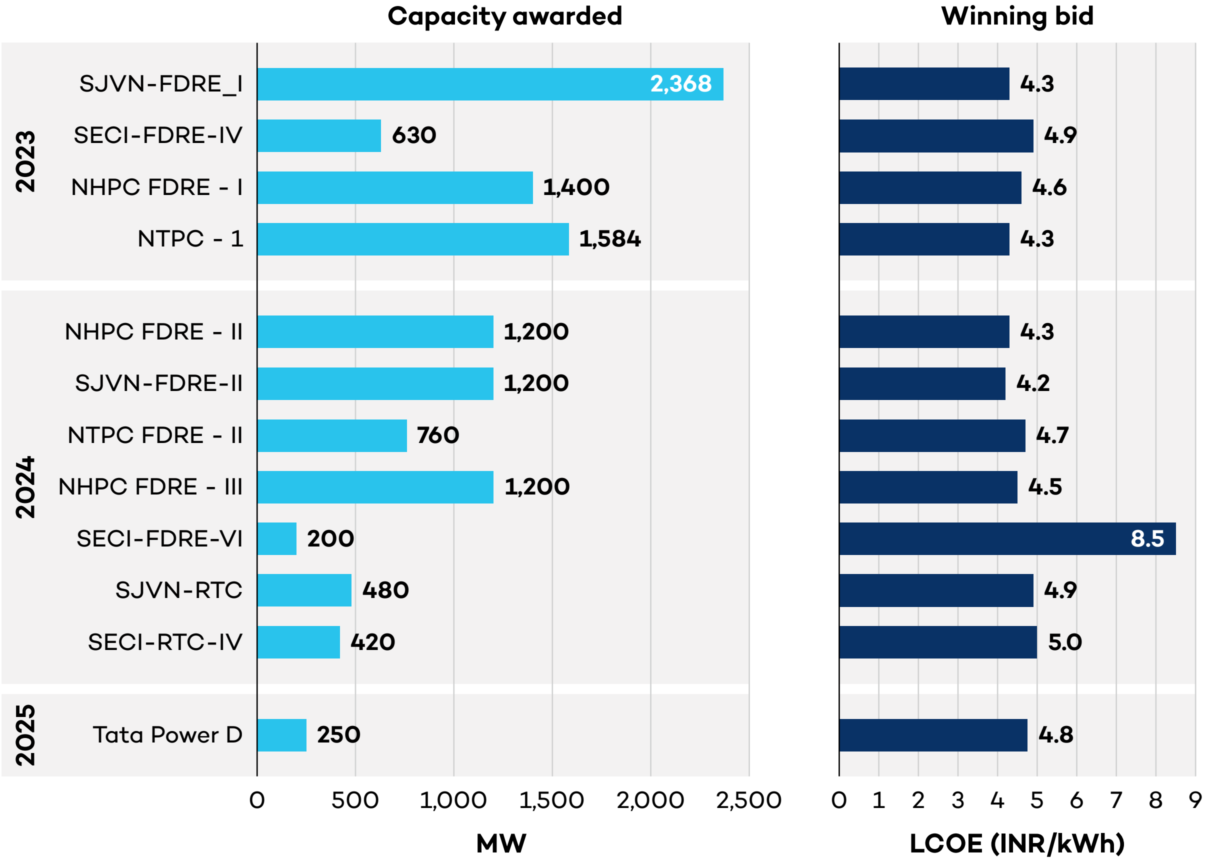
India's FDRE model marked a deliberate, policy-driven shift to make renewable power as reliable and dispatchable as thermal power. Further, it positioned the country as a pioneer in demand-driven renewable energy procurement, charting a course that could significantly reduce reliance on conventional thermal power (Srivastava & Rana, 2025).

2.3 Overview of the FDRE Tendering Landscape

Since the inception of FDRE in 2023, around 21 FDRE tenders, with a total capacity of approximately 29 GW, had been issued by various central agencies as of September 2025, including SECI, Satluj Jal Vidyut Nigam (SJVN), National Thermal Power Corporation (NTPC), and National Hydroelectric Power Corporation (NHPC). Seven tenders (totalling 9.6 GW) are under various stages of construction, while five tenders (totalling 2.1 GW) were awarded and are yet to begin construction. Four tenders are in their initial stages of the tendering process (totalling 3.9 GW)–three tenders are in the Request for Proposal (RfP) stage[3] (totalling 2.7 GW), while bidding is closed for one tender (1.2 GW). Five out of the 21 tenders were cancelled (totalling 4.2 GW). Of the 29 GW issued, 8.2 GW of capacity was not awarded. Figure 1 presents the timelines of all FDRE tenders that were awarded, while Figure 2 presents the status of implementation under different FDRE configurations.

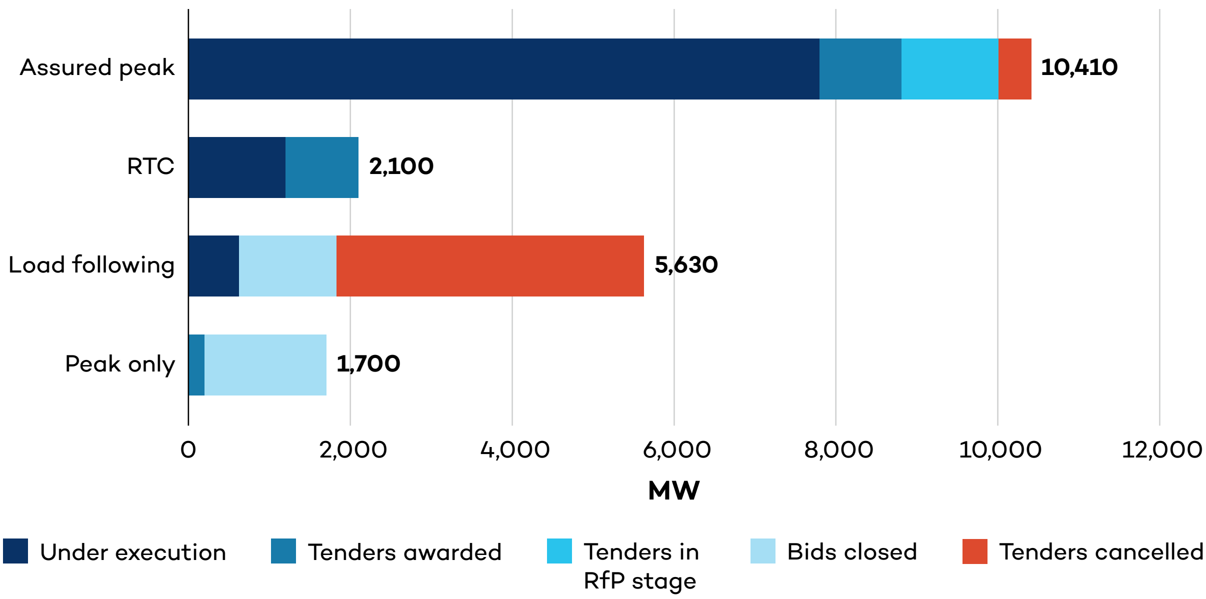
[3] An RfP is a formal document issued by a company to announce an upcoming project and invite potential vendors to bid on it.

Figure 1. Timeline and status of FDRE tenders awarded by central agencies



Source: Authors' compilation based on official FDRE tender documents.

Figure 2. Present status of FDRE tenders for different FDRE configurations



Source: Authors' analysis based on FDRE tender documents.

2.4 Impediments to Scaling FDRE

As a relatively new form of tendering, FDRE is experiencing some challenges. However, some of these are likely to be resolved over time as governments, discoms, and developers gain experience with the projects and adjust tenders and bids accordingly. Some challenges, however, may require more substantial reforms to accelerate deployment.

The mix of awards, cancellations, and active RfPs underscores both the momentum FDRE has gathered in a short span of time and the persistent hurdles that remain as it moves from policy vision to on-the-ground execution. To understand why nearly one seventh of announced FDRE capacity has been cancelled, it is important to examine the structural, market, and institutional impediments that have slowed its rollout. Key factors are discussed below.

2.4.1 High Costs Associated With DFR Thresholds

Achieving a 90% DFR requires oversizing both generation and storage capacities, which significantly increases the project's capital cost (see also Box 2 on DFR) (Rodrigues & Das, 2025). For instance, according to the ICRA, meeting the DFR requirements requires oversizing wind and solar by 2.5 to 3.5 times over the contracted capacity, significantly increasing the upfront capital investment (ICRA, 2024a). Unlike conventional energy projects, which incur most costs from operational or fuel expenses, renewable energy projects require most of their investment before commissioning (upfront investment). As a result, capital cost plays a key role in determining the levelized cost of electricity (LCOE). If balancing has to be done by developers at the individual plant level, it will always be more costly than at the aggregate level; ways to aggregate balancing for projects without necessarily depending on the transmission system operator or discoms must be considered.

2.4.2 Surplus Generation and Market Exposure

Oversizing capacity can cause FDRE projects to generate 25%–45% in excess electricity output (Rodrigues & Das, 2025). To recover value for uncontracted electricity generated, developers sell this surplus power in the DAM or real-time market without requiring prior consent from the procurer. Also, FDRE developers can sell the surplus power through bilateral contracts to any third party, without requiring a No Objection Certificate from the procurer (Sinha, 2024).

FDRE projects face two critical risks due to exposure to the wholesale electricity market: price cannibalization and market volatility. Price cannibalization occurs when large amounts of electricity generated during solar peak hours flood the wholesale electricity market, driving down prices and reducing revenues for renewable energy generators. Early signs of this effect are already visible in India. For instance, on August 23, 2024, prices dropped significantly during solar hours (with prices crashing to zero at times) (Goswami, 2025).

Market volatility adds an additional layer of risk. Analysis of DAM prices on the Indian Energy Exchange between 2021 and 2022 shows that the average revenue from surplus generation fluctuated by roughly INR 1/kWh (Rodrigues & Das, 2025). Even under conservative assumptions, such variation could lower developer revenues by 7%–13%, highlighting the importance of market design and risk-mitigation measures for FDRE deployment (Rodrigues & Das, 2025).

2.4.3 Land, Supply Chain, Infrastructure, and Regulatory Barriers

In addition, delays in signing of purchase and sale agreement, grid connectivity, and equipment procurement, in addition to supply chain constraints and a lack of skilled labour, impact project commissioning, which can significantly increase the overall capital cost (Agarwal et al., 2025). Land acquisition and land accessibility alone contribute to a 4% increase in the overall capital cost of FDRE projects (Grover, 2025; NR, 2025).

2.4.4 Financial and Institutional Constraints With Discoms

Developers are also concerned about the delayed payments from discoms. Many state-run discoms are financially strained, collectively owing power generators around INR 70,000 crore in total outstanding dues (as of September 2025). Between 2022 and 2023, only 15 out of 42 discoms saw an improvement in the average cost of supply and average revenue realization gaps; meanwhile, the gap continues to widen for others because of high power purchase costs and insufficient revenue realized from consumers (MoP, 2024a; PRS Legislative Research, 2022). Additionally, discoms are locked into long-term thermal PPAs (Garg & Shah, 2020). These PPAs include fixed capacity charges, a fixed amount to be paid irrespective of actual power drawn. This reduces flexibility for discoms in procuring power from newer sources (Shankar, 2024).

Moreover, thermal power provides firmness and fits within established scheduling and regulatory practices, which lowers the perceived risk for discoms (Shankar, 2024). In contrast, newer models, such as FDRE, despite becoming increasingly competitive, face administrative and financial hurdles because they are less familiar and disrupt existing relationships between state-owned discoms and thermal power generators.

Box 4. Valuing the full range of capacity and flexibility services that battery storage can provide

Unlike conventional generators, BESSs in India are currently remunerated as energy-delivery resources, not as capacity-providing assets. Stand-alone BESS tenders are typically compensated on an INR/MWh-month basis for usable stored energy, while hybrid or FDRE/RTC projects recover their costs through a single-part, levelized INR/kWh tariff that bundles renewable generation with storage dispatch. Storage is not paid through a tradable INR/MW-month capacity payment that reflects its contribution to system reliability in either case.

In contrast, TPPs recover fixed costs through a two-part tariff structure:

- a capacity (fixed) charge for availability (INR/MW-month) covering capital recovery, debt service, and operations and maintenance (O&M); and
- a variable (energy) charge for actual generation (INR/kWh) based on fuel consumed.

This asymmetry arises not from technical infeasibility but from institutional and legal design choices. Batteries can technically be contracted on an availability basis, but the current regulatory and contractual framework has yet to standardize the testing, certification, and measurement protocols required to support such payments.

Accurately determining the firm capacity of a battery requires well-defined tests for usable energy at declared depth-of-discharge and state of charge levels, round-trip efficiency, cycle-life limits, and augmentation commitments. Without long-term operational data and a standardized accreditation framework, regulators lack the evidence base needed to assign capacity credits to storage resources. Consequently, most BESS contracts use energy throughput as the payment metric rather than accredited capacity.

This structure also limits the contribution of FDRE projects to system-wide reserves. While FDREs provide firm, contracted supply to discoms through a bundled tariff, they do not yet ensure the availability of flexible capacity for ancillary or balancing services. Over time, however, FDRE contracts could be designed to require developers to allocate part of their storage capacity to system-level reserves, creating a bridge between project-level reliability and grid-wide adequacy.

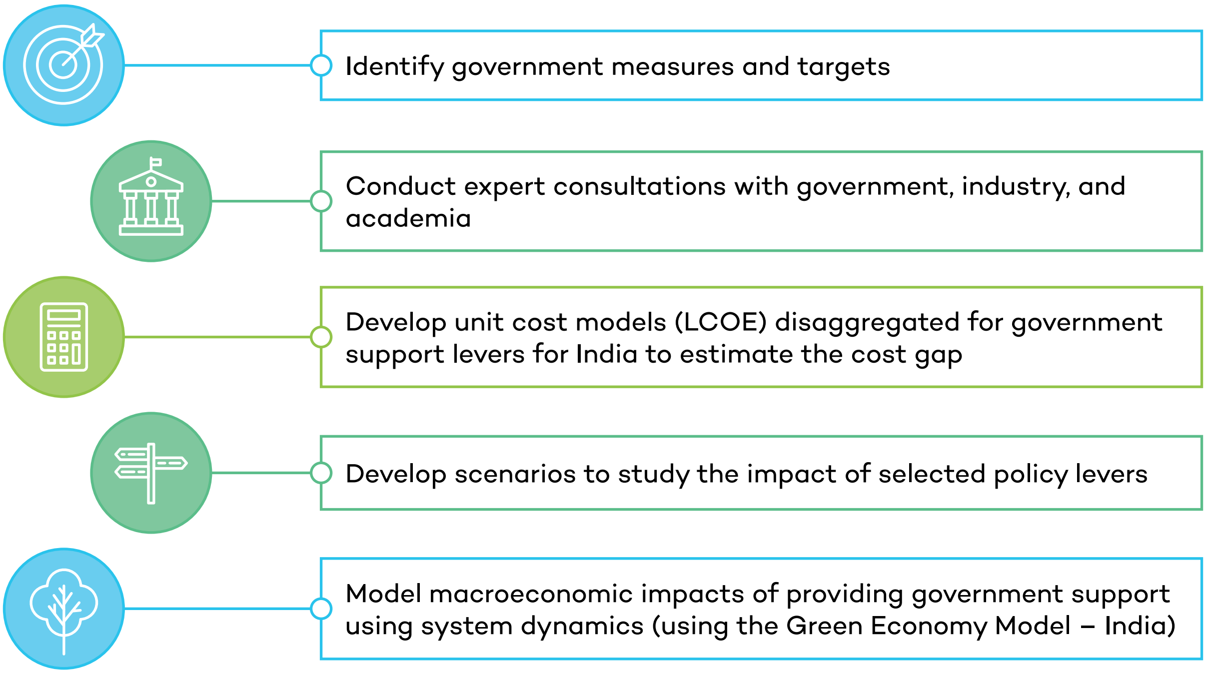
In the absence of this market maturity and legal scaffolding, India currently lacks a standardized, system-level mechanism to compensate storage for capacity provision in the way coal plants receive fixed charges.

This gap is likely to narrow, as India implements the *Guidelines for Resource Adequacy Planning Framework* (MoP, 2023a) and the *Draft Methodology for Capacity Credit of Generation Resources & Coincident Peak Requirement of Utilities Under Resource Adequacy Framework* (Central Electricity Authority [CEA], 2024). Together, these reforms could enable a more technology-neutral approach to reliability planning: valuing not only energy delivery but also capacity, ramping support, reserve provision, and ancillary services offered by storage.

3.0 Approach and Methodology

We used various methods combining quantitative and qualitative research to answer the research questions. Our methodology and major steps are summarized in Figure 3.

Figure 3. Summary of research methodology



Source: Raizada et al., 2024.

India is an early mover in enabling FDRE. Since FDRE is not a new technology but rather a tender-based solution, currently, no specific government support measures exist. However, FDRE projects can benefit from many government support measures that exist for solar, wind, and energy storage technologies in India. This report, for the first time, constructs and uses unit cost models of FDRE projects under different configurations to identify if existing but isolated government support measures for solar, wind, and energy storage are sufficient to cover the cost gap with existing benchmarks. The existing support measures for individual technologies (which constitute FDRE) are outlined in Box 5.

The study does not consider land constraints related to solar and wind plants that are part of the FDRE systems. While energy security, critical minerals requirements, and grid integration challenges related to FDRE capacity addition trajectory are some of the important aspects, they are not explored in the report.

Box 5. Government support measures for solar PV, BESS, and onshore wind

While FDRE has no stand-alone subsidy framework, these projects may still indirectly benefit from existing support measures for the underlying technologies. Some such measures include the following:

- **The Production Linked Incentive (PLI) scheme for solar PV and Advance Chemistry Cells**: Subsidies for domestic manufacturing of high-efficiency modules reduce module costs for developers, which could indirectly lower FDRE costs as well. Similarly, PLI for Advance Chemistry Cells could incentivize local manufacturing, with long-term potential to reduce energy storage costs relevant for FDRE.
- **Basic customs duty on solar PV**: The continuation of the basic customs duty (20% on solar cells and solar modules) is intended to bolster domestic manufacturing (Joshi, 2025). While this strengthens India's clean energy supply chains, it can temporarily raise capital costs for FDRE developers relying on imported components. Over time, as domestic capacity expands through PLI and related initiatives, these duties may support more stable and competitive input prices for FDRE projects.
- **Inter-State Transmission System (ISTS) Waiver**: Partial exemption of ISTS charges for solar and wind (until June 2028) can reduce grid-related costs for FDRE projects incorporating solar components. Further, the full waiver of ISTS charges for storage projects, extended until June 30, 2028, could benefit BESSs commissioned (within FDRE) before this date.
- **Approved List of Models and Manufacturers and Domestic Content Requirement (DCR)**: Domestic sourcing requirements support self-reliance but can increase costs for FDRE developers if lower-priced imports are unavailable.
- **Viability Gap Funding (VGF) scheme for BESSs**: Building on earlier VGF support for BESSs announced in 2023 (of INR 3,760 crore), the government approved a fresh tranche of INR 5,400 crore in June 2025 . This will support 30 GWh in BESSs and aims to attract INR 33,000 crore in investment by 2028. This provides capital support for grid-scale stand-alone BESS projects, but FDRE projects are currently not eligible.

Implications for FDRE

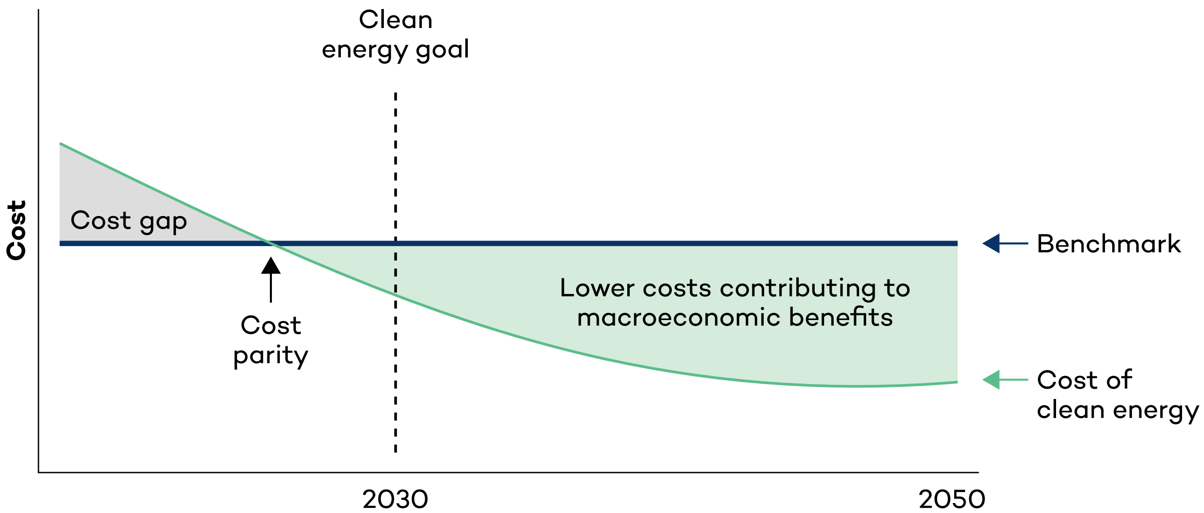
FDRE projects currently cannot access many of these measures directly, as certain schemes, such as the VGF for BESS, are restricted to stand-alone projects (i.e., storage-only projects). However, they may still derive indirect benefits through upstream cost reductions supported by the PLI scheme and lower transmission charges under the ISTS waiver (available until 2028), which can help narrow the cost gap. Further, extending storage-linked support, such as VGF for BESS, to FDRE projects could further enhance their economic competitiveness.

3.1 Quantitative Analysis

First, we determined whether FDRE is currently competitive with coal-fired power and, if not, when this might occur based on projected input costs to 2050. We estimated the cost of FDRE (based on the components of BESSs, solar, and wind) and compared this to a benchmark for coal-fired power. The study focuses on an annual time scale. The cost differential was calculated each year to 2050 as the marginal cost differential between one unit of energy from an FDRE project and a benchmark conventional equivalent (on a levelized basis).

We multiplied this per-unit cost difference by the number of units (i.e., MW capacity) needed per year to reach a target amount of FDRE (see Section 3.1.5 on adoption trajectory of FDRE) to calculate the size of the total "cost gap" (see Figure 4). The cost gap is representative of the size of government support needed to ensure FDRE is competitive with a conventional equivalent. Provision of public financial support can deliver economic benefits in terms of development, jobs, and lower pollution, particularly after cost parity has been reached. Some macroeconomic benefits begin earlier than cost parity, such as lower morbidity, mortality, and climate effects.

Figure 4. Conceptual approach to cost gap analysis



Source: Raizada et al., 2024.

Cost gap thus varies based on (i) the maturity of the technology (nascent technologies are typically more expensive relative to conventional equivalents), (ii) the size of the goal, and (iii) the chosen benchmark. We used India-specific data on costs and factored in expected falls in costs of production over time (based on technology learning rates).[4] The cost gap is distinct from an investment gap, which considers the total investment needed to achieve energy goals.

[4] FDRE costs decline over time due to learning effects across the underlying technologies: solar (Raizada et al., 2024), wind (CEA & Danish Energy Agency [DEA], 2022) and BESS (Raizada et al., 2024). While our projections to 2050 incorporate these learning rates, we did not optimize the evolving technology mix for FDRE across this period.

Equation 1. Estimating cost gap

$$\text{Costgap}_{\text{per year}} = \text{Lifetime generation}_{\text{annual addition}} \times (\text{LCOE}_{\text{benchmark}} - \text{LCOE}_{\text{FDRE}})$$

We define FDRE as a combined generation system using solar, onshore wind, and lithium-ion BESS storage[5] that can meet a given hourly demand profile with a predefined reliability (75% to 100%).

The government does not necessarily need to bridge the full cost gap. The outlay would vary depending on the assistance mechanism (such as direct transfers to developers, VGF, generation-based incentive, extension of transmission waivers), non-fiscal measures such as land provision, or transferring the costs onto the private sector and energy consumers through mandates. The financial assistance will directly impact the effective LCOE for FDRE and thus impact the cost gap for offtakers.

3.1.1 Selection of Wind–Solar–Storage Combinations for FDRE

The generation patterns of solar and wind vary significantly with time and location. This makes the CUFs for solar and wind critical parameters. Since CUFs differ by region, meeting a given demand profile for a particular location at a specified reliability level requires a tailored mix of solar, wind, and storage. In this study, we have designed the scenarios based on the solar–wind–storage combinations (Table 1) specified in the CEA report (CEA, 2024b). The CEA report looks at ways to provide RTC power to the discoms utilizing renewable energy sources along with storage, thereby enabling an increase in renewable capacity and achieving cost efficiencies, as well as meeting the Renewable Purchase Obligation (RPO) requirements of obligated entities. It considers the renewable energy RTC supply as a viable option. The report also indicates different demand patterns (flat, morning and evening 100% peak support, and commercial and industrial [C&I] customers) that are used for different case studies.

In this study, we simulate the LCOE for various technology combinations using CUF values and other parameters, as shown in Table 1 (CEA, 2024b). Simulation of diverse combinations of wind, solar, and storage helps us to account for the sensitivity of the FDRE LCOE to the combination mix to a certain extent. We estimate effective LCOE for all the cases (11) and consider the median for further analysis of the cost gap.

We use these CUFs to estimate the expected generation from solar and wind resources in different configurations. The case studies used in this study, based on the CEA report, aim to provide a steady power supply throughout the day (RTC) to meet three different hourly demand profiles: a flat load profile, a load profile with morning and evening peaks, and a two-shift demand profile of C&I consumers. However, FDRE can be useful in demand shifting, firming up the grid, or balancing grid stability.

[5] With a drastic decrease in the battery costs in the last few years, BESS is becoming cost competitive with pumped hydro storage (PHS) systems. Therefore, this study will be comparable when adapted for PHS as well. Moreover, compared to PHS, BESS is a more universal option as BESS do not have any specific geographical requirement.

Table 1. Combinations of wind, solar, and storage considered to estimate effective LCOE for FDRE

Sl. №	Case	Other details	Solar (MW)	Wind (MW)	Storage (MWh)
1	Case 1: RE RTC at 100% availability (flat demand profile of 100 MW)		184	370	402
2	Case 2: Case Study for 100 MW RE RTC @90% Daily availability with 2 hours morning & evening peak support		170	328	384
3	Case 3: 100 MW RE RTC suited for C&I customers		189	153	504
4	Case 4: 100 MW RE RTC with a state-specific solar and wind profile (100% reliability with flat load profile)	Tamil Nadu	500	303	1,410
5	Case 4: 100 MW RE RTC with a state-specific solar and wind profile (100% reliability with flat load profile)	Gujarat	323	398	678
6	Case 4: 100 MW RE RTC with a state-specific solar and wind profile (100% reliability with flat load profile)	Maharashtra	290	347	720
7	Case 4: 100 MW RE RTC with a state-specific solar and wind profile (100% reliability with flat load profile)	Gujarat and Rajasthan	466	212	1,194
8	Case 4: 100 MW RE RTC with a state-specific solar and wind profile (100% reliability with flat load profile)	Telangana and Tamil Nadu	500	166	1,332
9	Case 5: 100 MW RE RTC for C&I customers with a state-specific solar and wind profile	Gujarat	390	80	588
10	Case 5: 100 MW RE RTC for C&I customers with a state-specific solar and wind profile	Maharashtra	309	93	600
11	Case 5: 100 MW RE RTC for C&I customers with a state-specific solar and wind profile	Tamil Nadu	428	95	600

Note: RE = renewable energy.
Source: CEA, 2024b.

3.1.2 Annual Generation

Estimating annual generation is a critical step in estimating LCOE for FDRE. Annual generation can be estimated based on the case-specific installed capacity and CUFs of solar, wind, and storage. Annual generation is the total generation from the plant and consists of generation committed, generation sold additional (excess), and generation curtailed (ref. Equation 2, Equation 3, Equation 4, Equation 5, Equation 6, Equation 7, and Equation 8). Estimating the annual revenue from an FDRE plant can be complex because the developers may not be able to sell the entire expected generation from the plant. Our simulations show that FDRE plants designed to meet a specific demand profile typically produce some surplus generation beyond the committed amount. Developers include this excess to manage weather-related risks of low generation. As a result, developers can potentially earn revenue from two streams: the committed generation ($Revenue_{committed}$) and the excess generation ($Revenue_{additional}$).

PPAs signed before the final investment decision guarantee the sale of the committed generation. However, revenue from the excess generation remains uncertain, as selling this surplus in the open market can be challenging in terms of both demand for the electricity and the price gained. Therefore, in the context of FDRE, the standard definition of LCOE will not fully capture the economics of a hybrid system, as that will also depend on the extent to which the additional revenue (from the surplus sold in the market) offsets the total project cost. $Revenue_{additional}$ may also include earnings from other probable avenues like the capacity market and ancillary market and are expected to evolve with time.

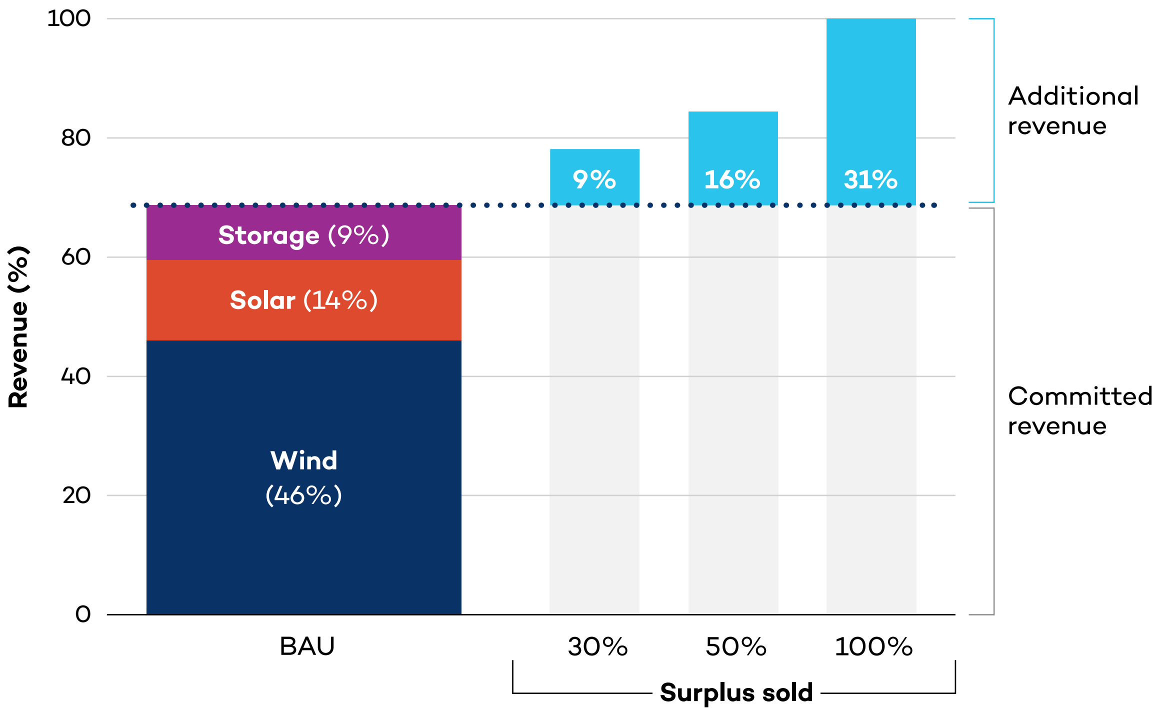
Therefore, while estimating $Revenue_{committed}$ for LCOE calculations, we consider only the electricity with guaranteed offtake under the contracted supply profile. A second revenue stream arises from selling a portion of the excess generation in the open energy market at an assumed price of INR 5.62/kWh.[6] The value of this revenue depends on how much surplus electricity is actually sold—for example, 30% of annual surplus generation in the 30% surplus-sold scenario and 100% in the optimistic 100% surplus-sold scenario. Based on stakeholder consultations, the 30% surplus-sold scenario is more realistic under current market conditions; however, tender-based prices observed in recent FDRE bids fall within the broader 30%–100% range. We also consider an intermediate 50% surplus-sold scenario and explore the possibility of higher revenues if developers can secure premium prices for a portion of surplus power or provide ancillary or capacity services.

Because these revenue streams materially change the net cost of FDRE, the cost metric varies across scenarios. To avoid misinterpretation, we use the term "effective LCOE" throughout this report. We define effective LCOE as the levelized cost of meeting the contracted FDRE supply after adjusting for any additional revenues realized from market-based sales of surplus energy or other system services. For the analysis presented in Section 4.3 below, this terminology also applies to the cost of thermal power. When we incorporate the cost of negative externalities (such as mortality, morbidity, and the cost of carbon) into the per-unit cost of coal-based

[6] We consider this rate based on the Indian Energy Exchange's average market clearing price for the year 2023 and assume it to be constant for simplicity, since future whole electricity prices depend on multiple variables.

electricity generation, its effective LCOE also increases. Here, an effective LCOE reflects a more comprehensive estimate of the true cost of producing electricity using coal power.

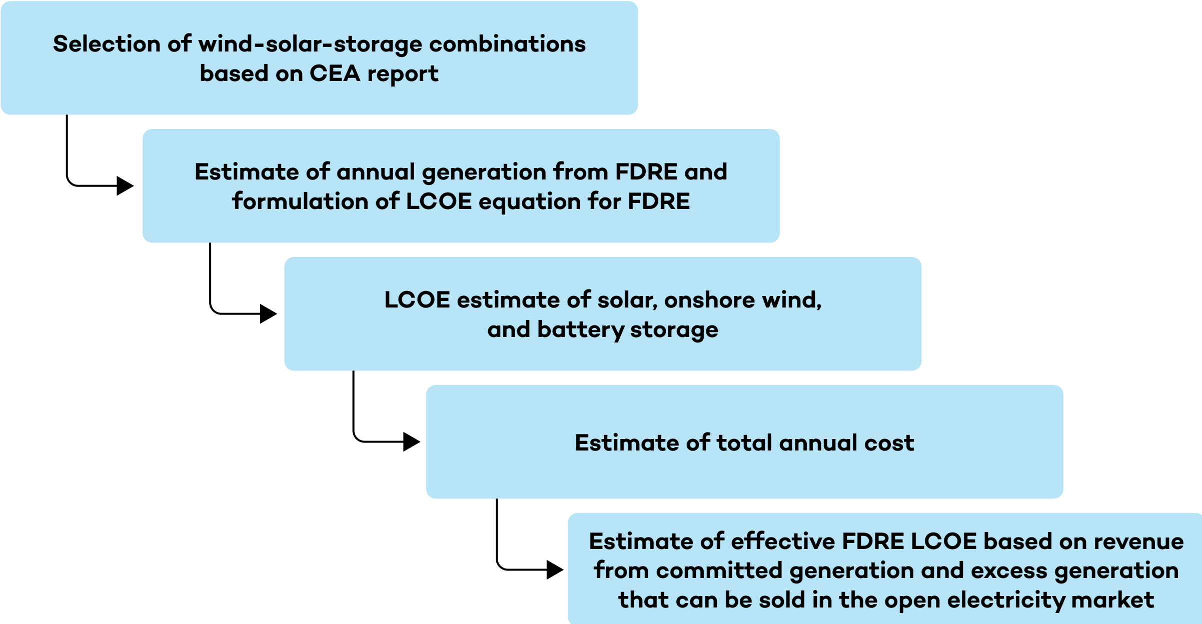
Figure 5. Scenario-wise revenue realization based on committed generation and the sale of surplus power in the open market



Source: Authors.

To calculate the cost gap at an economy-wide level, we calculate the blended effective LCOE for the several FDRE configurations discussed in previous sections. While LCOE may not be the perfect financial parameter for comparison of different resources with diverse properties, it is still the most widely used parameter for making investment and public finance decisions (Tongia, 2018). Figure 6 presents the methodology adopted to estimate the LCOE values for FDRE.

Figure 6. Methodology to estimate effective LCOE values for FDRE



Source: Authors.

We used Equation 2 to Equation 8 to estimate effective LCOE for FDRE:

Equation 2. Estimating annual solar power generation

$$\text{Solgen}_{\text{annual}} = \text{Capacity}_{\text{solar}} \times \text{CUF}_{\text{solar}} \times 8760$$

Equation 3. Estimating annual wind power generation

$$\text{Windgen}_{\text{annual}} = \text{Capacity}_{\text{wind}} \times \text{CUF}_{\text{wind}} \times 8760$$

Equation 4. Estimating annual storage requirement

$$\text{Storage use}_{\text{annual}} = \text{Capacity}_{\text{storage}} \times \text{CUF}_{\text{storage}} \times 8760$$

Equation 5. Estimating the total cost of the FDRE system

$$\text{Cost}_{\text{total}} = \text{LCOE}_{\text{solar}} \times \text{Solgen}_{\text{annual}} + \text{LCOE}_{\text{wind}} \times \text{Windgen}_{\text{annual}} + \text{LCOE}_{\text{storage}} \times \text{Storage use}_{\text{annual}}$$

Equation 6. Estimating the total generation

$$\text{Generation}_{\text{total}} = \text{Generation}_{\text{committed}} + \text{Generation sold}_{\text{additional}} + \text{Generation}_{\text{curtailed}}$$

Equation 7. Estimating the additional revenue from selling surplus electricity in the open market

$$\text{Revenue}_{\text{additional}} = 5.62 \times \text{Generation sold}_{\text{additional}}$$

Equation 8. Effective LCOE of FDRE

$$\text{LCOE}_{\text{FDRE}} = \frac{\text{Cost}_{\text{total}} - \text{Revenue}_{\text{additional}}}{\text{Generation}_{\text{committed}}}$$

3.1.3 LCOE Estimate of Solar, Onshore Wind, and Battery Storage

We estimate the solar and battery LCOE trajectories based on our earlier work (Raizada et al., 2024). The solar LCOE was modified to reflect the present market conditions, and we modified the battery LCOE estimate to exclude the input energy cost.[7] For estimating LCOE for onshore wind, we used the Financial Modelling of Offshore Wind model, which we previously applied for offshore wind (Raizada et al., 2024). However, it is important to highlight that the economics of onshore wind differ substantially from offshore, particularly with respect to capital expenditure (CapEx) and CUFs. In this study, all assumptions (CapEx, O&M, CUF, and lifetime) are derived from CEA's onshore wind technology catalogue (CEA & DEA, 2022), and they are clearly summarized in Appendix B.

3.1.4 Benchmarking Effective FDRE LCOE Against TPPs

Comparing effective FDRE LCOE directly with the LCOE of conventional plants can be challenging. In India, TPPs enjoy a two-part tariff: capacity charges based on availability and energy charges for the actual energy supplied. TPPs are also allowed to pass on any variations in fuel (coal) prices to end consumers through the Fuel and Power Purchase Cost Adjustment mechanism. FDRE tariffs, on the other hand, are generally single-part tariffs and expected to absorb any cost fluctuations throughout the PPA life cycle. Despite having less cost variability than coal power facilities, FDRE initiatives carry financial risks associated with possible fluctuations in market prices and unpredictability surrounding future battery expenses. Regulatory obstacles and challenges with grid integration may lead to delays and increase the overall capital costs. Additionally, if developers have less than the expected generation due to climate variability, their revenue gets impacted. An exception was the RTC-1 tender, which allowed a 3% annual tariff escalation for the first 15 years. From a technical standpoint too, FDRE projects represent a different approach to reliability: instead of relying on continuous coal burn, they combine renewable energy generation with storage to deliver firm, dispatchable power, offering cleaner ramping capability.

However, since FDRE projects in India are expected to compete with new coal-fired TPPs on a levelized cost basis, we used the LCOE of new coal plants in this study as the relevant

[7] The LCOE estimate in our previous report included the input energy cost as well. However, in a combined wind–solar–storage system, considering the input cost will result in double counting of input energy cost.

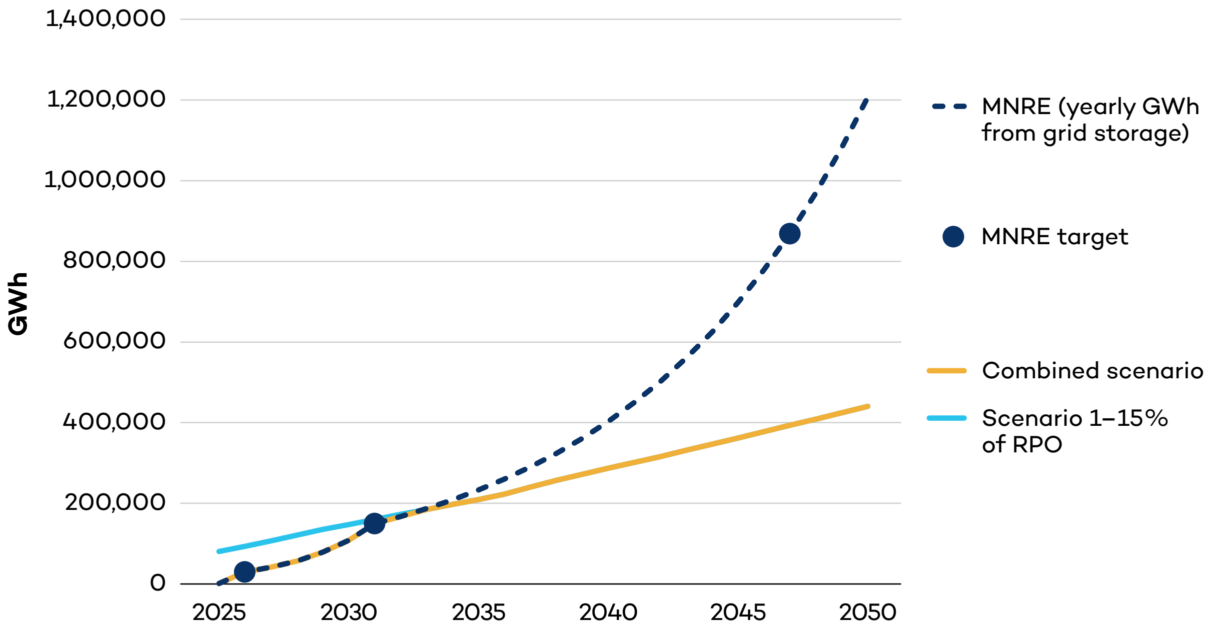
benchmarks. We therefore selected a 2023-commissioned coal plant located in a pithead region[8] (from NITI Aayog) and used its LCOE, as reported on the Merit website (MoP, 2025b), as our benchmark (NITI Aayog, n.d.). We then used the simulated effective LCOE of FDRE systems to compare against electricity prices from these new pithead coal-fired thermal plants (MoP, 2025b).[9]

3.1.5 Adoption Trajectory of FDRE

We estimated the FDRE adoption trajectory based on demand projections from the Green Economy Model (GEM), assumed RPO pathways, and the assumed share of FDRE within the RPO targets. To define the RPO pathways, we started by assuming that India's entire electricity demand will be met by renewable energy by 2060. This assumption also aligns with India's net-zero target for 2070 and the electricity sector's relative readiness for decarbonization.

We also aligned FDRE capacity additions through 2030 with the grid storage expansion projected by the Ministry of New & Renewable Energy (MNRE). We found that in 2030, the FDRE capacity estimated based on MNRE storage target aligns with the 15% of wind–solar RPO target value. Hence, for the period beyond 2030, we assume that FDRE plants will contribute 15% of the wind–solar RPO target (Figure 7).

Figure 7. FDRE adoption trajectory



Source: Authors.

[8] Coal plants can be located at the site of the coal mine (pithead) or away from the coal mine (non-pithead). The majority of new coal plants are pithead because this reduces coal transport costs, which can be substantial.

[9] MERIT (Merit Order Dispatch of Electricity for Rejuvenation of Income and Transparency) is a platform established by the MoP, Government of India, in partnership with POSOCO and CEA. It offers insights into the merit order dispatch of electricity, with the goal of enhancing power procurement efficiency and fostering transparency within the power sector. The platform presents information such as daily state-specific marginal variable costs for generators, power purchases by state, and explanations for deviations from the merit order.

3.2 Cost Gap

We estimated the cost gap based on the lifetime generation of FDRE plants and the difference in LCOEs (Equation 9). We applied a discount rate of 8% to arrive at the discounted cost gap values.

Equation 9. Estimating the cost gap

$$\text{Costgap}_{\text{per year}} = \text{Lifetime generation}_{\text{annual addition}} \times (\text{LCOE}_{\text{benchmark}} - \text{LCOE}_{\text{FDRE}})$$

3.3 Externalities of Coal-Based Thermal Power

Coal-based thermal power imposes significant external costs on society, which are not reflected in electricity tariffs but are borne through deteriorating public health, productivity losses, and environmental degradation. These externalities need to be considered in a like-for-like cost comparison with FDRE, which does not have combustion-related emissions.

We therefore developed a second benchmark that incorporates the health and climate impacts of coal. For health-related costs, we included premature mortality and lost productivity due to air pollution. For climate-related costs, we included the social cost of carbon (SCC) arising from coal-based TPPs—that is, a carbon price. These represent real, measurable economic and societal costs, even if they are not paid directly through electricity bills. By internalizing these externalities into the benchmark LCOE for coal, we provide a truer reflection of its societal cost to better inform long-term energy investment decisions. The assumptions are shown in our detailed assessment of externalities in Appendix C.

3.4 Macroeconomic Impacts

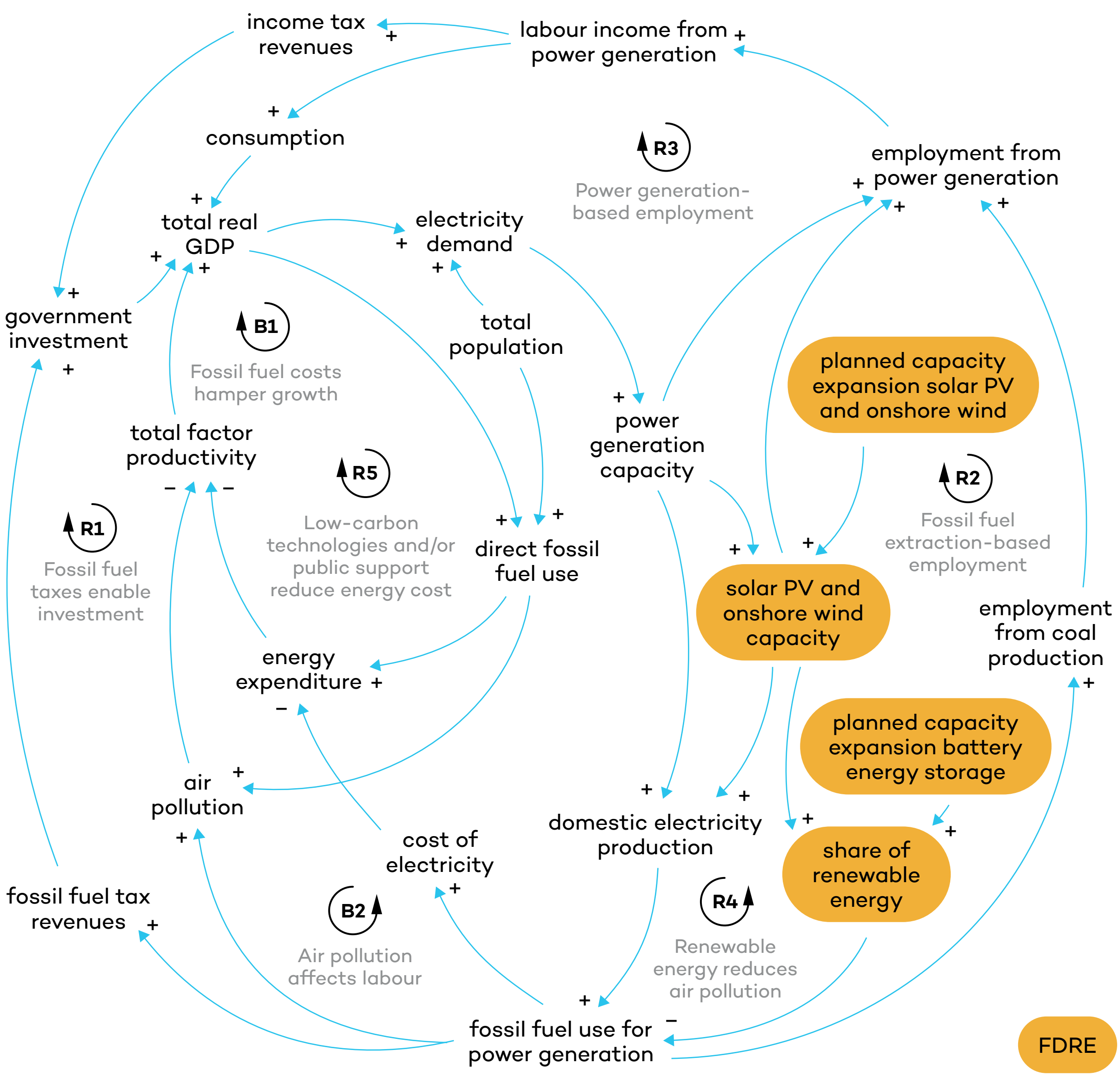
We employed an integrated energy–economy–environment model (GEM) to estimate the impact of meeting government targets for FDRE on power generation, job creation, air pollution, GHG emissions, energy spending, economic productivity and GDP, and government revenues and expenditures. The scenarios analyzed also explored the possible allocation of public funding to address the cost gap associated with transitioning to FDRE, when it emerges.

The GEM was expanded to account for electricity production from FDRE and was already adapted to the national context. We find this model to be particularly suited to project how the deployment of FDRE, characterized by the integration of renewable energy generation with energy storage and grid flexibility, affects economic growth via reductions in air pollution and GHG emissions, changes in energy spending, and employment creation.

We performed a systemic analysis for the assessment of BESSs, wind, and solar PV (Raizada et al., 2024). We present this in the causal loop diagram illustrated in Figure 8. In the context of FDRE, economic activity is shaped by energy expenditure (driven by consumption patterns and the cost structure of FDRE in relation to coal power generation under different scenarios), air quality improvements (resulting from reduced fossil fuel reliance), and employment dynamics (arising from increased construction and O&M of FDRE infrastructure).

The economic impact of FDRE deployment also depends on the levelized cost of new technologies, which affects energy spending. If FDRE solutions entail higher costs, this may exert downward pressure on GDP unless offset by targeted government support. Conversely, if FDRE technologies achieve cost parity or savings compared to conventional generation, they can provide an additional boost to economic performance. In addition to the levelized costs, macroeconomic benefits emerge from air pollution reduction, and hence higher labour productivity.

Figure 8. Causal loop diagram on the systemic approach for macroeconomic analysis



Source: Authors.

3.5 Qualitative Analysis

To validate our study design, assumptions, and results, we conducted eight interviews with government officials, national think tanks, project developers, electricity regulators, distribution companies, and investors. These interviews and consultations helped us understand the evolving tender designs for FDRE and effective policy levers for further studying the cost gap.

4.0 Results

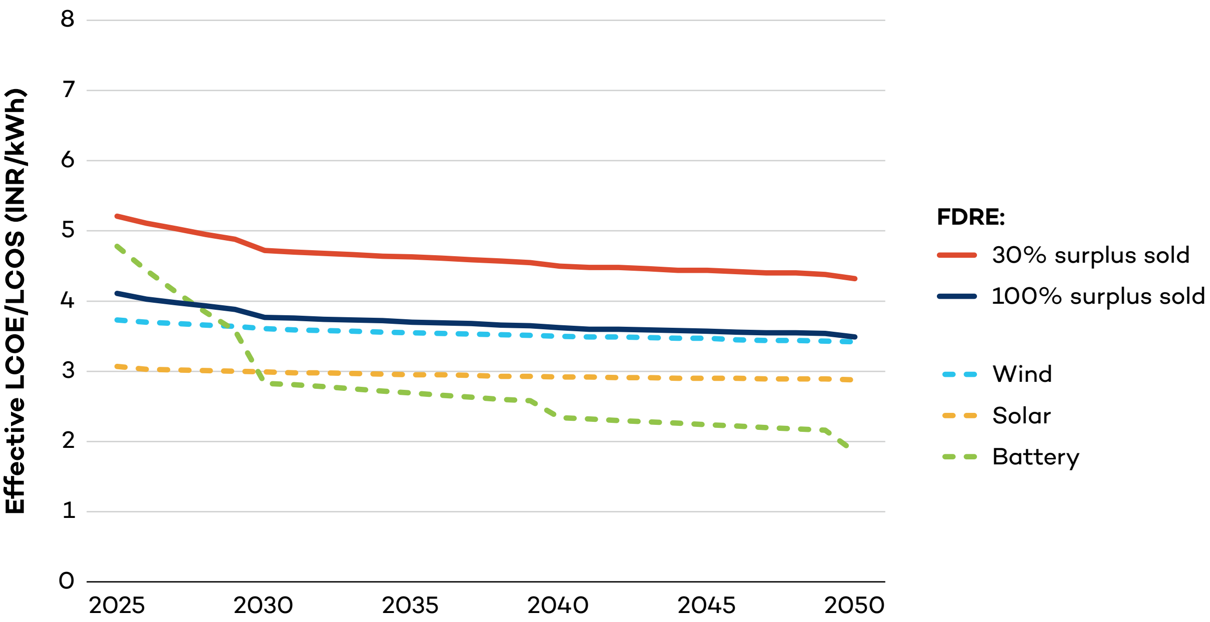
4.1 Effective LCOE for FDRE

We estimated the effective FDRE LCOE for all cases mentioned in the CEA report. The various combinations of wind–solar–storage are listed in Table 1 in Section 2 on methodology. We simulated the LCOE for each of the above cases under two different scenarios:

1. **30% surplus-sold scenario** – assuming only 30% of the excess generation (beyond the guaranteed generation) is sold in the open electricity market.
2. **100% surplus-sold scenario** – assuming 100% of the excess generation (beyond the guaranteed generation) is sold in the open electricity market.

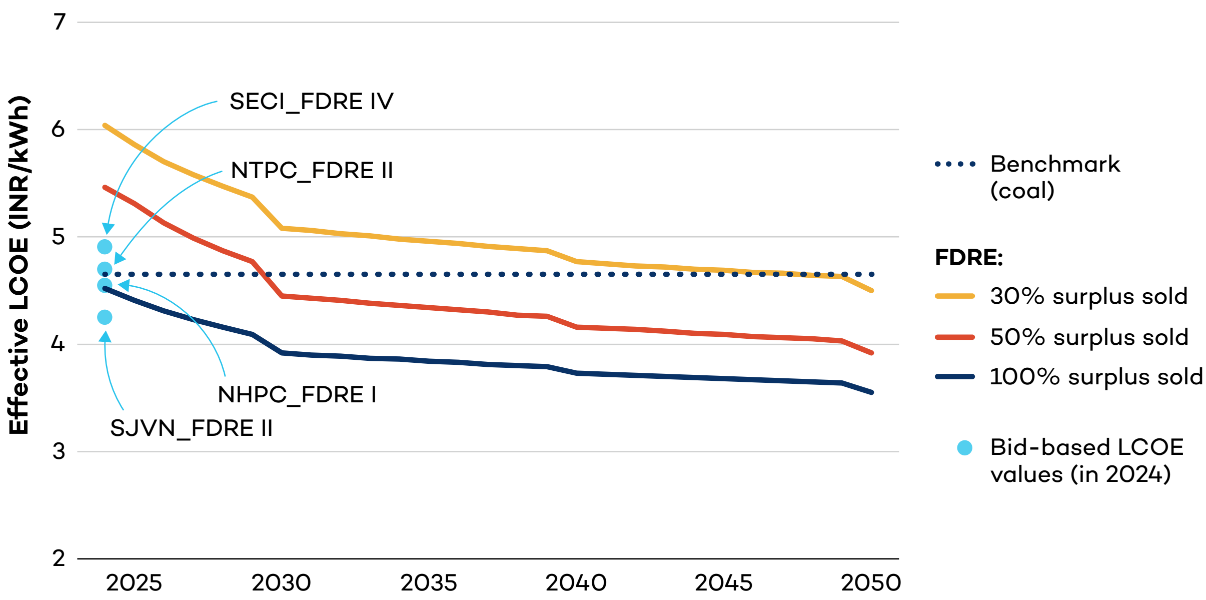
Figure 9 presents the typical effective LCOEs (Case 1) estimated for the 30% surplus-sold scenario (Table 1). We then estimated the median LCOE across all 11 cases in each scenario to arrive at the two effective LCOE scenarios. Figure 10 shows the LCOEs (dots) from recently finalized bids for validation. Figure 10 also shows a 50% surplus-sold LCOE scenario (red line) when 50% of the excess generation gets sold in the open electricity market. We find that the simulated effective FDRE LCOEs broadly align with the range observed in recent tender-based LCOEs. However, it is important to highlight that the effective LCOE for FDRE is higher than BESS, solar, or wind because of the need for over-capacity to achieve the specified CUF levels.

Figure 9. Typical effective LCOE estimated in case 1: 30% surplus-sold and 100% surplus-sold scenarios



Source: Authors.

Figure 10. Validating simulated effective LCOEs for FDRE with several recently finalized bid-based LCOE values



Source: Authors.

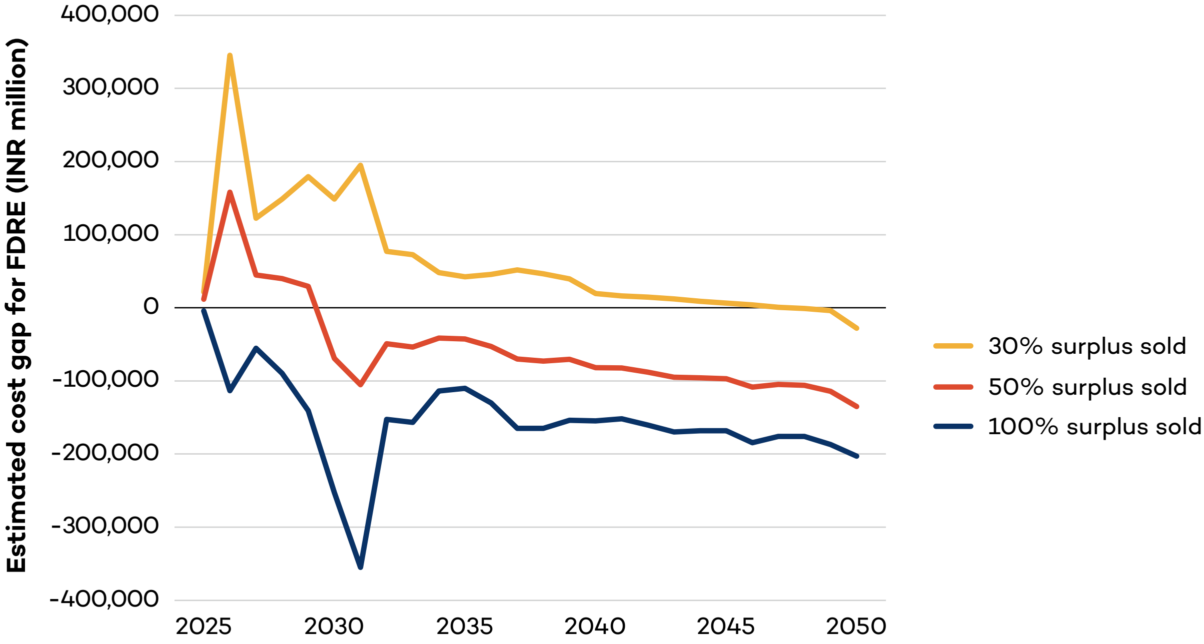
4.2 Estimating the Cost Gap for FDRE

As outlined in the methodology chapter, we used a new pithead coal-fired thermal plant LCOE as the benchmark. As per the Government of India's revised SHAKTI Policy, the government will promote setting up Greenfield Thermal Power Projects primarily at pithead sites (i.e., nearer to the coal source) (Cabinet Committee on Economic Affairs, 2025). Hence, we compared effective FDRE LCOE with new pithead plants. Combining the benchmark with the three simulated effective LCOEs (30%, 50%, and 100% surplus sold), we created three scenarios for cost gap estimation, and the results are presented in Figure 11.

Our analysis shows that while FDRE is already cost competitive with new coal-fired thermal plants under the 100% surplus-sold scenario (100% of non-contracted generation sold), if 50% of non-contracted excess generation gets sold in the market (represented by LCOE for the 50% surplus-sold scenario in Figure 10), FDRE reaches cost parity by 2030.

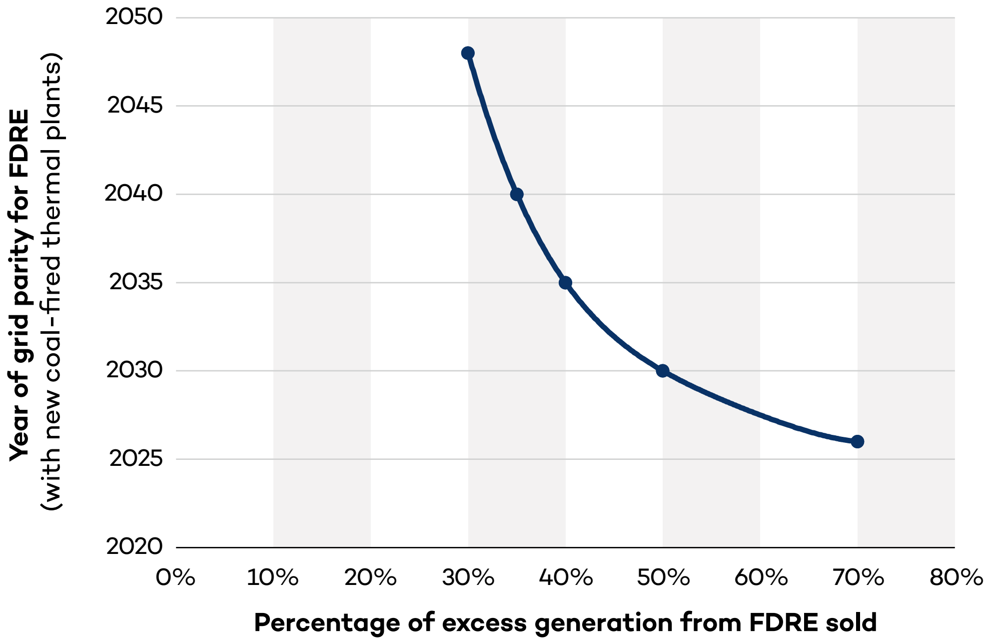
However, the new thermal plants remain more economical than FDRE under the 30% surplus-sold scenario (30% of non-contracted generation sold). The cost gap narrows over time as the learning rates for BESS, solar, and wind result in falling FDRE costs. FDRE reaches cost parity with new pithead coal plants by 2048. We held the benchmark cost of coal constant, due to uncertainty over future coal prices. The year-on-year cost gap patterns (Figure 11) observed in all cases depend on the unit cost gap and the annual expected capacity addition. In line with the grid storage expansion projected by the MNRE, we have assumed faster progress in FDRE capacity additions through 2030. Beyond 2030, we assume the capacity addition to be slow and steady.

Figure 11. Cost gap estimation for 100%, 50% and 30% surplus sold scenarios



Source: Authors.

Figure 12. The year of grid parity for FDRE depends on the share of excess generation from FDRE that could be sold in the open electricity market

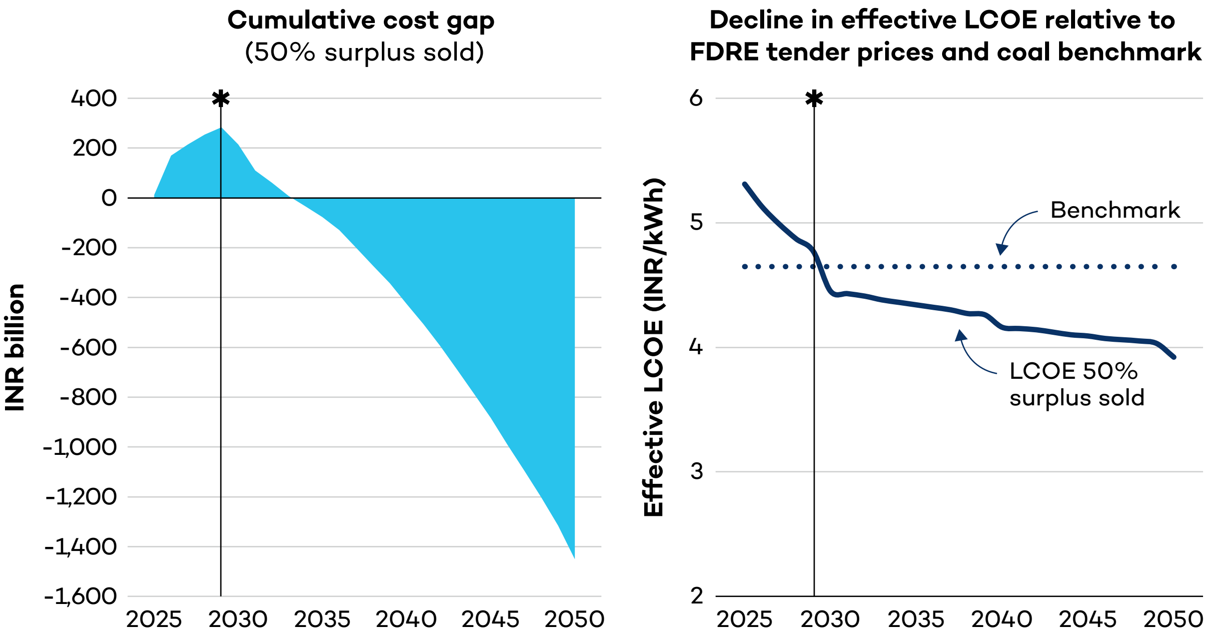


Source: Authors.

Building on the cost gap estimation, we calculated the year when the effective FDRE LCOE would reach cost parity with new coal-fired thermal plants assuming varying proportions of excess generation sold in the open electricity market. This proportion can be seen as a reflection of the market price that such excess generation can fetch. Figure 12 illustrates how the year of cost parity shifts depending on the share of excess FDRE generation that can be absorbed by the market at an assumed electricity price of INR 5.62 /kWh. For example, if any FDRE plant could sell 40% of its excess generation in the open market at a per-unit cost of INR 5.62, the plant would reach parity with the new coal-fired thermal plants by 2035 (noting that the benchmark coal price is held constant).

Figure 13 demonstrates how FDRE LCOE's crossover with the benchmark LCOE impacts the cumulative cost gap. The cumulative cost gap peak coincides with the LCOE crossover and starts to reduce. However, for the cumulative cost gap to turn positive, it takes another three years.

Figure 13. Impact of the FDRE benchmark/LCOE crossover on the cumulative cost gap



✱ 2029: Effective LCOE crosses the benchmark.

Source: Authors.

4.3 Externalities

We estimated a small number of externalities associated with coal combustion: mortality and morbidity associated with air pollution, and climate change from carbon dioxide (CO_2) released (Table 2). These are a small subset of the full externalities associated with coal, which on a life-cycle basis would include emissions associated with mining, transport, and construction. We used conservative values, and therefore our results should be considered lower-bound estimates. The assumptions and detailed results are shown in Appendix C.

Table 2. Estimated externalities associated with coal combustion in India

Externality	Metric	Cost per kWh (INR)	Cost per kWh (USD)
Morbidity	Lost working days due to air pollution-related illness	0.04	0.0004
Mortality	Premature deaths due to air pollution	3.69	0.04
Climate change	Cost of carbon (USD 49/tonne)	4.81	0.05
Total		**8.54**	**0.1**

Source: Authors' calculations, based on sources in Appendix C.

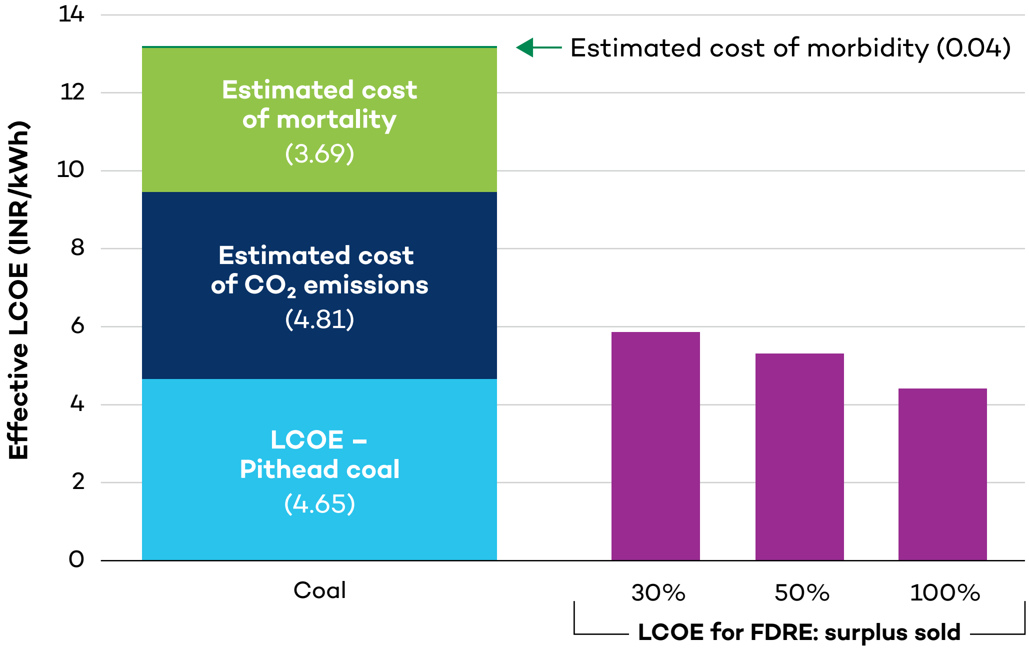
Our results are conservative compared to the International Monetary Fund, which estimated "implicit subsidies" for coal of USD 9.71/kWh arising from costs associated with air pollution and climate change (International Monetary Fund, n.d.). This fiscal support for coal-fired power plants places a strain on public finances, which could otherwise be redirected toward the acceleration of FDRE technologies.

These costs represent real outlays by governments and society, such as health care costs related to air pollution-induced illnesses, loss of productivity, crop losses, and infrastructure damages associated with climate change. They are not an intangible economic concept but rather a real prospect for deteriorating fiscal balances, value addition, and employment. Figure 14 compares the estimated effective LCOE between new pithead coal and FDRE across three surplus-sold scenarios. Without accounting for externalities, coal appears cheaper at INR 4.65/kWh (USD 0.05/kWh) compared to FDRE's INR 5.86/kWh (USD 0.06/kWh) under the 30% surplus-sold scenario in 2025, with competitiveness achieved only under the 100% surplus-sold case.

However, this changes dramatically once externalities are included. Adding morbidity impacts (INR 0.04/kWh) has only a modest effect, but factoring in mortality costs (INR 3.69/kWh) significantly raises the cost of coal. The increase becomes even starker when CO_2 emissions are incorporated (INR 4.81/kWh), pushing the effective LCOE of pithead coal to INR 13.19/kWh (USD 0.14/kWh) as shown in Figure 14. At this point, FDRE is already more competitive than coal, even under the 30% surplus-sold case.

This step-by-step inclusion of external costs shows how the apparent cost advantage of coal erodes once its broader social and environmental damages are considered. It is also important to highlight that the cost of inaction on climate change means that the SCC is expected to rise over time, which will only widen this competitiveness gap further in favour of FDRE.

Figure 14. Cost competitiveness of FDRE vs. coal (after factoring in externalities cost associated with thermal power generation)



Source: Authors.

This data implies that once externalities are factored into the cost equation, FDRE would not require any additional public financial support to compete with coal.

The challenge, therefore, shifts from closing a financial gap for FDRE to ensuring that these external costs are accurately reflected in coal pricing through instruments such as carbon pricing or targeted taxation. Embedding such costs into market signals is essential to steer investment and procurement decisions toward pathways that align with India's long-term social, economic, and environmental objectives.

The Central Government has attempted to use regulatory approaches that follow the polluter-pays principle by requiring TPPs to make investments that would reduce toxic air pollution. However, these efforts have stalled, presumably due to cost impacts. Chief among these was the mandated installation of pollution-control technologies, such as flue gas desulphurization (FGD) units, aimed at curbing sulphur dioxide emissions. While these retrofits were intended to mitigate air pollution and reduce public health impacts, they significantly increase the capital and operating costs of coal-based generation. Box 6 examines how FGD retrofitting could reshape the economics of thermal power, and these costs further strengthen the relative case for FDRE (Box 6).

Beyond cost implications, coal-fired plants also face persistent time and implementation disadvantages. Long gestation periods, construction delays, and complex regulatory approvals extend commissioning timelines and inflate tariffs, further diminishing coal's attractiveness in comparison to renewable-based dispatchable options. These challenges are detailed in Box 7, which contrasts the commissioning timelines of coal and FDRE projects and highlights the latter's faster deployment and standardized procurement structure.

Box 6. FGD retrofitting costs, exemptions, and the FDRE advantage

The cost dynamics of coal power plants would be fundamentally altered by the regulatory push to reduce emissions by retrofitting pollution-control technologies. FGD is a pollution-control technology mandated by India's environmental regulations to curb sulphur dioxide (SO_2) emissions from TPPs aimed specifically at reducing the harmful health and environmental impacts of SO_2.

FGD retrofitting adds significantly to both capital and operating costs. Installation costs typically range between INR 1.9 million and INR 9 million per MW, depending on the size of the plant, location, and number of units in the project. The additional CapEx can raise the LCOE for thermal power in the range of INR 0.11–0.30/kWh (USD 0.0012–0.003/kWh) (Ani, 2025, p. 202; Majumdar et al., 2025; PowerLine, 2021). Additional recurring costs, including reagents (limestone supply), sludge handling and disposal, and increased auxiliary power consumption to run the FGD system, further add to the overall LCOE.

To mitigate the financial impact on electricity-generating companies, India's CERC treats FGD installation as a "change in law" event, allowing cost pass-through via tariff revisions. While this shields generators, it exposes discoms and consumers to increased tariffs and cost volatility, undermining long-term power affordability and price stability.

Recent amendments to FGD exempted 78% of 537 TPPs from FGD installation, based on distance from populated urban areas (Bhattacharji, 2025). As per some estimates, it will reduce the average cost of electricity supply by INR 0.25–0.30/kWh (USD 0.002–0.003/kWh) (Business Standard, 2025). However, such relaxations come at a significant public health cost. Full FGD implementation across India's coal fleet could cut particulate matter ($PM_{2.5}$) emissions by 8% and reduce premature deaths by 17% annually (Shende et al., 2024). This raises questions about balancing short-term cost benefits with long-term health implications.

Box 7. Timelines for commissioning new coal pithead plants and FDRE

Coal-fired power plants typically face longer gestation periods and commissioning timelines compared to renewable energy projects, owing to complex approvals, land acquisition hurdles, and extensive construction requirements. Recent coal plant projects in India show commissioning timelines ranging between 5 and 7 years from the signing of the PPA (Worrall et al., 2018). For instance, Torrent Power's recent 1.6 GW ultra-super-critical coal power project in Madhya Pradesh is scheduled to be commissioned in 72 months (Parikh, 2025). Similarly, a brownfield expansion project with two units of 800 MW at Chandrapur (Jharkhand), carried as a joint venture between Coal India and DVC, is expected to take 38 months after the Letter of Award to complete construction and commissioning (TNN, 2025).

Beyond longer gestation periods, delays often push commissioning further, driving up the tariffs. The Tamil Nadu Generation and Distribution Company's (TANGEDCO) 1.6 GW Uppur project faced a 3-year delay from its initial 3-year engineering, procurement, and construction schedule, leading to increased tariffs for discoms that are already financially burdened (Shah, 2021). On the ancillary side, coal-fired power plants face additional regulatory and technical challenges that add to the timelines. Challenges in land acquisition and environmental clearances further add to the timelines of commissioning.

By contrast, FDRE tenders have structured and rigid timelines. In FDRE tenders, developers are required to supply power within 24 months of the effective date of the PPA for projects not more than 1,000 MW and 30 months for projects more than 1,000 MW (MoP, 2023b). For instance, the SECI's RTC tender (SECI-RTC-IV, 1,200 MW) is explicitly set to be available 24 months from the contract to commence supply, with a 6-month grace period subject to additional penalties (Gupta, 2024).

These shorter, enforceable schedules reflect the modularity of renewable components, standardized procurement, and parallel development processes that characterize FDRE projects. While challenges in grid interconnection and land acquisition remain, addressing bottlenecks in grid interconnection and land acquisition processes could accelerate the commissioning process for FDRE projects (Grover, 2025), as they are narrower in scope and duration than for coal. As a result, FDRE not only delivers faster but also reduces exposure to cost escalation and regulatory uncertainty, which are key advantages in a capital-constrained power system.

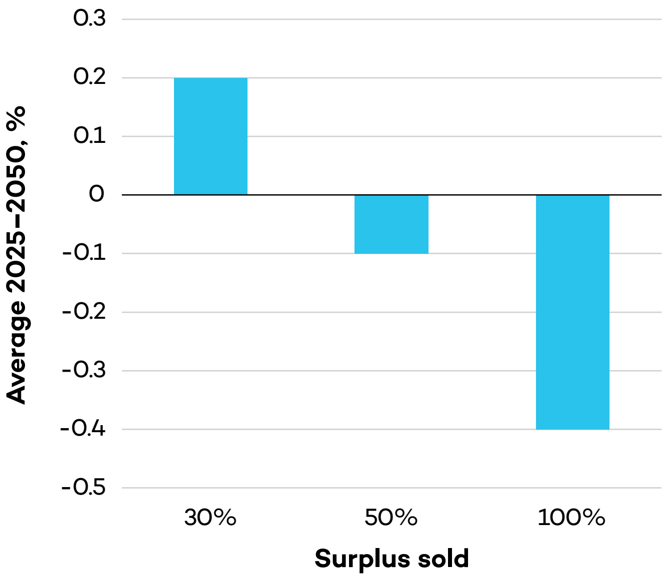
4.4 Macroeconomic Results

We created three main simulations to analyze the macroeconomic performance of FDRE, in accordance with the assumptions used for the levelized cost calculations. Specifically, we noted that depending on the cost assumptions used and the benchmark considered, FDRE may result in additional costs (30% surplus-sold scenario) or net savings (100% surplus-sold scenario). In the 50% surplus-sold scenario, 2030 is the threshold year: net costs emerge before 2030, while net savings are accrued after. In essence, FDRE is more expensive than new pithead TPPs with 30% surplus-sold assumptions or cheaper with 100% surplus-sold assumptions. The cumulative cost gap reaches as high as INR 1,636 billion in the 30% surplus-sold scenario, but a savings of INR 4,060 billion emerge in the 100% surplus-sold scenario. Net savings of INR 1,451 billion are reached instead in the 50% surplus-sold scenario. These results consider only the cost gap between the coal benchmark (new pithead coal without externalities) and our three FDRE estimates.

The scenario with 100% surplus-sold results in immediate cost savings from the first year of implementation, the 50% surplus-sold scenario cost savings start in 2030, and the 30% surplus-sold scenario generates net cost savings starting in 2048. This indicates that public support may be required, at least for the short term, to stimulate FDRE adoption, assuming 50% or less of the excess power generated can be sold. Alternatively, other policies would be needed (discussed in Section 5).

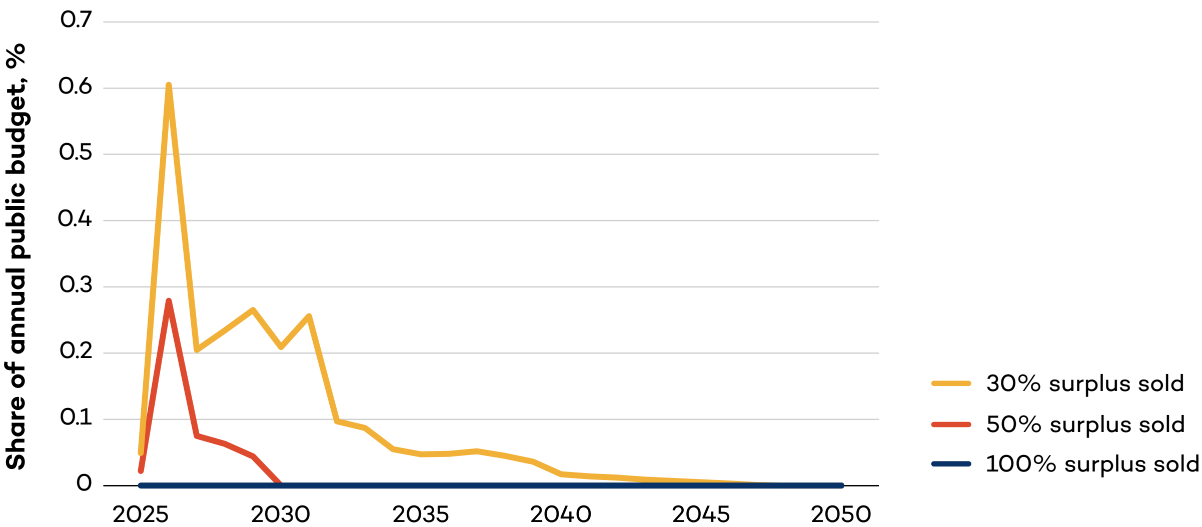
The introduction of FDRE has macroeconomic implications, especially for energy spending, jobs, and GDP. In relation to energy spending, FDRE could result in an average reduction in national energy spending in the range of 0.4% of the energy bill or INR 55.1 billion in the 100% surplus-sold scenario, declining to 0.1% and INR 19.7 billion in the 50% offtake scenario, or an increase of 0.2% or INR 22.2 billion in the 30% offtake scenario (Figure 15).

Figure 15. Impact of FDRE adoption on the energy bill, average 2025–2050



Source: Authors.

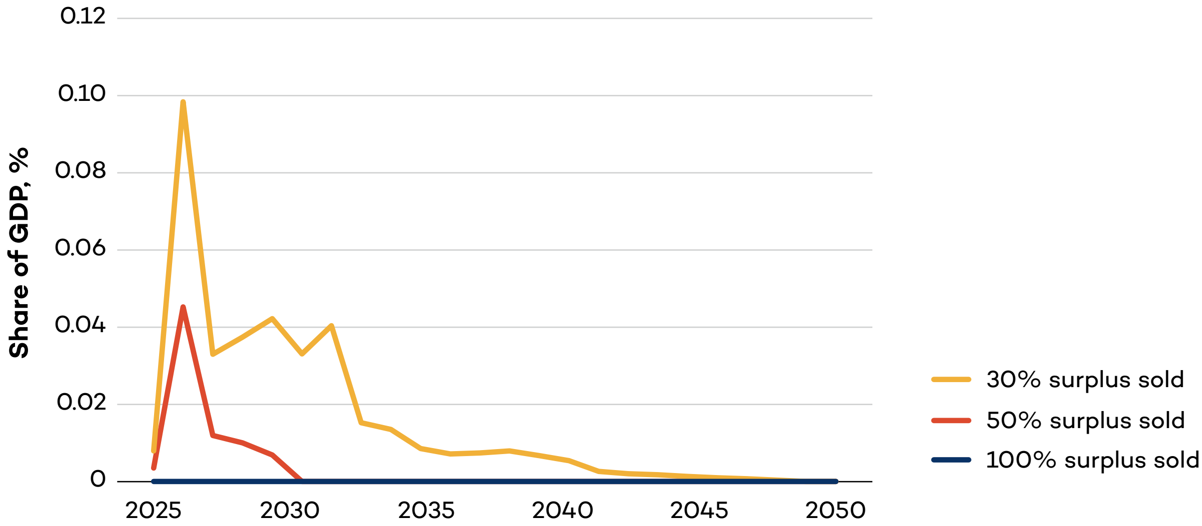
Figure 16. Required FDRE support, as a share of the public budget



Source: Authors.

If public support were to be used to limit energy cost increases under the 30% and 50% surplus-sold scenarios, government funding to bridge the cost gap was projected to reach 0.09% of the current budget and 0.01% of GDP per year on average between 2025 and 2050 (30% surplus-sold scenario). Figure 16 and Figure 17 show these annual requirements over time. For the 30% surplus-sold scenario, 0.26% of the public budget will be required between 2025 and 2030, which will then decline to 0.07% between 2030 and 2040. When compared to GDP instead, the funding required reaches 0.04% between 2025 and 2030 and declines to 0.01% for the period 2030–2040. As a result, most of the support is required in the short and medium terms. Minimal support is required in the 50% surplus-sold scenario, with 0.02% of the current budget on average, with a peak at 0.28% in 2026 and no support required from 2030. No support is required in the 100% surplus-sold scenario.

Figure 17. Required FDRE public support, as a share of GDP



Source: Authors.

FDRE is forecasted to generate net job increases. Additional jobs from solar, wind, and battery storage reach up to 81,450, 4,820, and 26,150 jobs in 2050, respectively. This adds up to 112,420 jobs in 2050. These estimates include both construction and installation, and O&M. O&M jobs become progressively more important over time, representing 15% of total job creation in 2025 but growing to 83% by 2050.

Conversely, job losses from coal power generation amount to 48,400 jobs in 2050, including both construction and O&M. That said, jobs lost in the mining value chain for coal are not considered, and neither are jobs lost or gained in the value chain of critical minerals for battery storage and solar PV.

On the aggregate, net job creation from FDRE reaches 64,000 jobs in 2050, with an average value between 2025 and 2050 of 43,400 jobs. Induced job creation should be added on top of this value, as a result of the FDRE-induced increased economic activity (i.e., via changes in energy spending and labour productivity). Induced job creation reaches 1.145 million jobs in 2050, with an average value for 2025–2050 of 708,260 jobs. By 2050, 10 induced jobs are created for each direct and indirect FDRE job (Table 3). The induced jobs included in Table 3 are the jobs created as a result of macroeconomic impacts (i.e., because of GDP being higher when we use FDRE instead of coal-powered plants to produce electricity). If FDRE pushes GDP higher, there will be more investment in the economy and more jobs being created across sectors. We do not consider the value chain jobs for the sourcing of coal. Similarly, we do not consider jobs in the full value chain of FDRE.

Table 3. Employment creation from FDRE generation and losses from coal substitution

Year	FDRE employment (jobs created per year)					Jobs lost in thermal power generation	Net employment: FDRE vs. coal	Net employment (with induced jobs)
	Solar	Wind	Storage	Induced jobs	Total employment			
2025	1,532	36	630	-	2,198	398	1,800	1,800
2030	41,768	1,517	15,815	127,648	186,749	15,904	43,197	170,845
2050	81,449	4,822	26,147	1,033,048	1,145,467	48,396	64,023	1,097,071

Source: Authors.

Finally, as indicated above, FDRE is forecasted to generate positive impacts on GDP. Two main factors affect GDP as a result of FDRE adoption: changes to energy spending and a reduction in air pollution, which subsequently affects human health and labour productivity. GDP impacts are visible across all scenarios and range between INR 118,600 billion cumulatively or INR 4,740 billion per year on average (30% surplus-sold scenario) and INR 119,750 billion cumulatively, or INR 4,790 billion per year on average (100% surplus-sold scenario). The cumulative increase in GDP to 2050 corresponds to approximately 62% of current GDP; on an annual basis, instead, FDRE would result in GDP being 0.5% higher in the year 2032, 1% higher by 2038, and 1.8% higher by 2050.

Overall, from a macroeconomic perspective, FDRE results in higher economic growth and net job creation. It also contributes to a reduction in GHG emissions and air pollutants. It is economically viable in the short term when considering the 100% surplus-sold scenario and will become viable by 2030 in the 50% surplus-sold scenario and by 2048 in the 30% surplus-sold scenario. When considering the avoided cost of emissions and air pollution, it generates net societal value even in the 30% surplus-sold scenario. In other words, the avoided costs of health and climate change externalities presented above result in economic productivity increases with the adoption of FDRE. Higher productivity, especially for labour, increases GDP, generating a second gain for society: one is the cost reduction when FDRE is adopted, and the second is additional economic growth resulting from higher labour productivity, obtained from a reduction in health and climate costs.

5.0 Discussion

FDRE in India is a tender-driven construct. Scaling FDRE hinges on developers managing risks that stem from high upfront capital costs, uncertain revenues from surplus power sales, penalties, exposure to wholesale price volatility, and the limited appetite of discoms locked into thermal PPAs. India's current support ecosystem (ISTS waivers, PLI, and manufacturing-linked incentives) reduces upstream costs, but it does not provide direct risk cover for firmed renewable energy procurement.

We were unable to ascertain how developers approach these risks in their tendering or operations due to commercial confidentiality. From consultations, we found that developers typically assume 0% surplus-sold for tariff bidding to manage risks; any additional surplus-sold beyond the level is an upside for investors. However, the tariffs obtained in FDRE tenders—all below our 30% surplus-sold LCOE and one below the 100% surplus-sold LCOE—suggest that developers who take up FDRE tenders are confident that projects can break even.

We also need to consider alternative explanations for our results. Our effective LCOE estimates may not fully reflect actual costs—this could be due to the underlying estimates for solar, wind, and BESS, or assumptions related to oversizing. It is also possible that developers face lower costs than we have projected. Another plausible explanation is that developers may not be oversizing their installations to the extent we modelled. Consultations suggest that some developers might prefer to incur occasional penalty costs rather than invest in additional capacity that ensures penalties never occur. However, we were unable to access data on the extent to which existing FDRE contracts have triggered penalties for failing to meet DFR requirements. That said, our estimates are based on India-specific data and have been tested with experts, giving us confidence in their robustness.

FDRE has clear advantages over coal when social costs are included. Cost competitiveness improved dramatically when factoring in only three of the many externalities associated with coal-fired power. FDRE becomes cheaper than coal immediately under all scenarios. FDRE can attract a premium for its lower emissions profile. Rather than just selling in the open market at power exchange, developers should seek other markets like carbon markets or corporate PPAs, where companies are willing to pay a premium for firm, renewable power.

However, the model has pros and cons like all energy solutions. The need to oversize capacity is inefficient and may not necessarily lead to lower system-wide costs if the surplus capacity is monetized by higher price spreads. The surplus energy at peak times, such as midday solar, may have limited monetization options, increasing risks and financial burdens on developers. FDRE tenders could strain land use, resource allocation, and transmission infrastructure, yet deliver only contractual minimums in terms of dispatchable power.

Governments should therefore discern and promote the most appropriate type of clean energy based on system needs. FDRE can be prioritized where energy is needed to fit a specific demand profile (the DFR) and peak needs. Balancing responsibilities is increasingly being pushed onto developers, even in Europe. For instance, under Redispatch 2.0 in

Germany (in force since October 2021), all generation plants of 100 kW and above (including renewables and storage) must participate in redispatch. Plant operators are obliged to provide planning and real-time data, update forecasts (day-ahead and intraday), calculate downtime, and allow grid operators to control or curtail output to ease congestion and enhance flexibility. This shows that, much like in India, developers in Europe are also taking on more responsibility for load management, though via regulatory redispatch obligations rather than bundled supply contracts.

Otherwise, strong emphasis should be on procuring standard solar and wind projects together (hybrid) with strategically sited stand-alone ESSs to deliver system flexibility and firming services more cost-effectively than integrated FDRE projects.

Stand-alone storage can be sized independently and deployed at locations that maximize value (congestion relief, local reliability, peak shaving), enabling

1. more efficient utilization of capital—storage can be sized exactly for the required firming rather than oversized to meet burdensome DFR targets.
2. better system integration and dispatch flexibility, as storage can respond to grid needsdynamically.
3. multiple revenue streams—capacity, energy arbitrage, ancillary services—particularly as markets mature.

Solar-plus-BESS is emerging as the most cost-effective solution for short-duration balancing and peak demand management (Box 8), while FDRE is better suited for delivering firm, 24×7 renewable power at scale. Solar-plus-BESS and FDRE will play complementary roles in India's energy transition.

Box 8. Solar-plus-BESS and FDRE: Complementary pathways

FDRE is one of a suite of options the Government of India offers discoms to contract for firmed renewables and manage VRE. Additionally, the rapid decline in battery storage costs has spurred significant momentum for solar-plus-BESS projects in India, with costs falling by over 50%–60% between November 2023 and April 2025 (Chojkiewicz et al., 2025). This sharp decline has enabled solar-plus-BESS to achieve record-breaking bids. For instance, a reverse auction in May 2025 set a record-low tariff of INR 3.32 per unit for Solar + 4-hour ESS in an SJVN Ltd tender, which combined 1,200 MW solar with 600 MW/2,400 MWh storage. The resulting tariffs are now substantially comparable to wind–solar hybrid auctions (JMK Research & Analytics, 2025).

Modelling studies have projected that a solar-plus-storage system in India could already—theoretically—deliver 24x7 clean power at over 95% availability for less than INR 6/kWh (Chojkiewicz et al., 2025). This is similar to or lower than current tariffs in most states and tariffs for new coal power plants. With further declines expected in both solar PV technologies and BESS, the competitiveness of solar-plus-storage will only improve relative to coal. However, while attractive for short-duration firming (e.g., evening peak coverage), solar-plus-BESS alone faces limitations in achieving true RTC supply without significant system oversizing and storage scaling (Rutter, 2025).

FDRE tenders include wind, which is expensive relative to solar. The proportion of solar, wind, and BESS capacity is location specific, as is the renewable energy generated in each location.[10] For instance, when wind generation achieves a CUF above ~31%, hybrid systems combining solar, wind, and storage become more cost-effective than stand-alone solar-plus-BESS for 24×7 supply (Rutter, 2025). Even at moderate wind CUFs (~25%), adding a proportion of wind generation (for example, a wind–solar ratio of 1:5 to 1:7) lowers the overall system cost by reducing the need for oversized storage.

5.1 Alternative Procurement and Financial Support Pathways for Firmed Renewable Energy

Several countries have experimented with innovative procurement and financial support mechanisms that do not necessarily subsidize generation directly but instead stabilize revenues to de-risk investments in firmed renewables. Contracts for Difference (CfDs) provide long-term price certainty to renewable energy developers, reducing exposure to market volatility and easing access to project finance (Department for Energy Security and Net Zero, 2022). Australia's Capacity Investment Scheme (CIS) ensures dispatchable generation capacity through availability-linked tenders aligned with the retirement of thermal assets (Shah, 2025). Capacity market models, such as the Pennsylvania-New Jersey-Maryland (PJM) Interconnection and the Independent Electricity System Operator (IESO) models in the United States and Canada, respectively, offer procedural lessons for designing procurement frameworks. This section outlines their design features, performance requirements, market impacts, and potential insights from these mechanisms for strengthening FDRE.

5.1.1 Contracts for Difference

The CfD mechanism addresses the risk of revenue instability for renewable energy generators and shields the consumers by ensuring predictable cash flows. This mechanism operates via a two-way, long-term hedging contract between the renewable energy generator and an offtaker (usually, a government-backed entity) that guarantees a "strike price"[11] to the generators, insulating them from wholesale market swings (in electricity prices). If the market price dips below the strike price, the offtaker entity compensates the renewable energy developers. Conversely, during high market prices, the excess revenue generated by the renewable energy developer is returned to the offtaker. This mechanism allows for the efficient use of public funds and avoids overpayments (Ason & Poz, 2024).

[10] FDRE costs also decline over time due to learning effects across all the underlying technologies (solar, wind, and BESS). While our projections to 2050 incorporated these learning rates, we did not optimize the evolving technology mix for FDRE across this period.

[11] Strike price is a fixed per-MWh price that is agreed through the CfD's competitive bidding process. This represents the minimum revenue developers require to finance the project. For instance, from all the accepted bids, the highest accepted bid becomes the "clearing" strike price for all the winning bids. This uniformity is ensured to encourage honest bidding among the renewable energy developers and simplifies the process, where everyone is paid the same, despite fluctuations in the market price.

Similar to the CfD mechanism, India has implemented a Virtual Power Purchase Agreement (VPPA) mechanism. This mechanism aims to reduce financial instability among renewable energy generators and facilitate the acceleration of large-scale renewable energy deployment by adhering to the RPO/Renewable Consumption Obligation (RCO) target. A VPPA is a bilateral agreement between a power producer (developer) and an offtaker (buyer). In this arrangement, the developer injects power into the wholesale markets, such as DAM and real-time market. The offtaker and generator settle the financial difference between a pre-agreed "VPPA price" (strike) and the market price. Additionally, the offtaker receives Renewable Energy Certificate, which can be used in sustainability reporting. RPO/RCO targets are compliance mechanisms, and large power consumers opt for standard solar/wind over hybrid systems to procure power, which is less expensive. This hinders the investments made in ESSs and demand flexibility (Das & Rodrigues, 2025).

- **Evidence of success**: CfDs are most widely known for their success in the development of offshore wind in the United Kingdom, where they drove down costs from GBP 150/MWh to GBP 37.35/MWh between 2014 and 2024 while protecting consumers from overpayment (Mayo, 2024).
- **Why it matters to FDRE**: CfD could also be explored as an instrument for FDRE in India (particularly, for the sale of excess generated power in the volatile market). Embedding a CfD-style "price floor" for FDRE surplus power would provide revenue stability, lower the cost of capital, and allow investors to plan around guaranteed minimum earnings.

India now has a clearer path to both administered and market-settled CfDs, given the Securities and Exchange Board of India (SEBI)–CERC framework[12] for power derivatives and ongoing approvals for electricity futures on Multi Commodity Exchange of India and National Stock Exchange (from July 2025) (Ahuja & Yadav, 2025; PowerLine Magazine, 2025; The Times of India, 2025b). However, framing CfDs as financial instruments subject to SEBI's supervision also risks misalignment with energy-sector objectives and could create unnecessary regulatory complexity. There will need to be real-time surveillance and seamless coordination between SEBI and CERC, as any miscommunication or lag in action could have ripple effects, raising costs for electricity consumers and undermining market integrity (Awasthy, 2025). Power-sector regulators like CERC might be best positioned to administer energy-specific mechanisms grounded in grid reliability and sectoral strategy.

Despite various advantages, CfDs face the following challenges:

- During prolonged low market prices, the government is responsible for bearing the financial responsibilities, which raises concerns about long-term fiscal sustainability.
- Competitive bidding could push the strike price so low in auctions that developers make unsustainable cost cuts that disrupt or overlook local supply chain investments, community benefits, and domestic manufacturing.
- Once strike prices are determined, adjusting these elements can be slow, making it challenging to respond to fluctuations in capital costs or inflation.

[12] After a landmark judgement by the Hon. Supreme Court of India in 2021, electricity markets have split jurisdiction: the CERC oversees spot contracts, while SEBI regulates derivatives.

5.1.2 Australia's Capacity Investment Scheme

Australia's CIS is a federal mechanism that incentivizes VRE and firm dispatchable capacity, like battery storage, by underwriting private investments (Shah, 2025). Launched in 2023, CIS rolls out competitive tenders for clean energy and storage to i) support grid reliability, ii) meet peak demand using renewable energy technologies, and iii) accelerate renewable energy deployment to replace retiring coal power plants (ASL, n.d.).

The CIS is like FDRE in that it provides flexibility to renewable energy developers to combine solar, wind, and storage in any configuration, but the contract approach does not require developers to invest in both generation and storage for every project, nor do the VRE+BESS projects aim to provide 24x7 power. While some long-duration storage (e.g., 8-hour batteries) has been supported, most awarded projects are 4-hour systems (Department of Climate Change, Energy, the Environment, and Water, 2025). There are two types of contracts (Zhou et al., 2024):

- **Generation CIS Agreements**: Renewables-only; minimum annual availability, with rebates for shortfalls (if a project fails to meet this minimum availability threshold, the project proponent may be required to repay part of the revenue support they received under the scheme).
- **Clean dispatchable Generation CIS Agreements**: Renewables paired with storage; minimum level of operational storage capacity to enable dispatchability, and annual availability threshold of 90% with rebates for shortfalls.

The CIS model operates by the same principle as CfD's "floor–ceiling" concept. For instance, if the market price falls below an agreed floor price, the government compensates the renewable energy developer for the shortfall. Conversely, if the revenue exceeds the ceiling price, the renewable energy developer pays the excess to the government. This helps in reducing exposure to the volatility of wholesale market prices for the renewable energy developers (Colthorpe, 2024).

5.1.3 PJM Interconnection and IESO Procurement Models

India's electricity market is largely driven by long-term PPAs and government procurement through agencies like SECI and state discoms. There is no centralized mechanism where all load-serving entities procure capacity obligations in advance. However, as India aims to increase its renewable energy penetration, a capacity-based market is imperative to ensure system reliability and long-term adequacy. A key driver in a capacity market model is the resource adequacy—the ability of a system to have enough available generation to always meet electricity demand. In 2023, the MoP and CEA introduced resource adequacy guidelines to help states plan for capacity additions up to FY 2035 (CEA, 2024a). However, these remain planning tools and still depend on bilateral tenders for implementation. Thus, India remains at a pre-market stage where capacity valuations are being formalized while market instruments are still not in place.

Capacity markets require mature forecasting systems, robust market oversight, and financially sound distribution companies capable of entering forward commitments, which are lacking presently in India. An immediate focus could be to enhance the existing procurement models, like FDRE, and progressively build on the capacity market.

Models of capacity markets, particularly the PJM Interconnection and the IESO, offer procedural lessons for designing future-ready procurement frameworks. PJM secures capacity through forward auctions: its first auctions, called the Base Residual Auctions, are run 3 years ahead of its delivery. They are followed by Incremental Auctions, which allow for capacity adjustments closer to delivery to reflect the revised demand conditions (Sustainable FERC Project, n.d.). This rolling tender process significantly mitigates the risk of locking in capacity that may not align with the actual system needs. The Effective Load Carrying Capability is a critical tool used in PJM to measure a resource's ability to provide reliable power when needed.

IESO adopts a hybrid approach to ensure the required capacity is met through a blend of short-term annual capacity auctions and long-term RfPs. The short-term auctions provide flexibility in adapting to changing demands, and the long-term procurements ensure firm capacity is secured (Ashraf, 2024).

5.1.4 Lessons for FDRE

India could consider introducing a revenue-stabilization mechanism similar to a "floor–ceiling" mechanism to de-risk developers and provide greater revenue certainty. This would incentivize the adoption of FDRE technologies and help keep consumer electricity prices affordable. CfD and CIS frameworks provide financial certainty to ensure investor confidence.

FDRE tenders can integrate lessons from PJM and IESO by

1. embedding Effective Load Carrying Capability capacity metrics to improve how reliability contributions are valued.[13]
2. introducing multi-horizon procurement with shorter forward tenders complemented by long-term commitments to provide flexibility and investor confidence, while also preparing for an eventual capacity market.

5.2 Overcoming Other Barriers to the Competitiveness of Firmed Renewables

Additional policy changes and cost trends could undermine the competitiveness of firmed renewables:

1. Local content requirements (Approved List of Models and Manufacturers and DCR) and trade barriers, such as customs duties on solar panels, can push up domestic prices.
2. Subsidy schemes that currently support solar, wind, and BESS (such as VGF or ISTS waivers) will sunset, raising project costs further.

[13] Effective Load Carrying Capability is a probabilistic capacity metric that determines a resource's contribution to system reliability.

3. Input costs, such as components and critical minerals, could erode the profitability of new projects.
4. Challenges and rising costs in acquiring land, particularly land for wind close to transmission substations, will add to overall project costs.

To address these risks while sustaining momentum for firmed renewable energy, India may need a calibrated policy approach. Potential measures include gradually phasing DCR in a way that supports domestic manufacturing without unduly inflating project costs; redesigning financial support mechanisms (e.g., moving from blanket subsidies to performance-based incentives for firm capacity); and securing diversified supply chains for critical minerals and components through trade partnerships and strategic reserves. In parallel, fostering a robust domestic storage manufacturing ecosystem, building on the PLI scheme, would reduce vulnerability to global price shocks. Taken together, such measures could help ensure that the cost advantages of firmed renewables are not eroded, preserving their central role in India's net-zero transition.

6.0 Recommendations

The Government of India can consider several policy measures to support clean energy technologies that would benefit FDRE:

1. Continue to develop and deepen the wholesale electricity market to enable energy storage projects to access multiple revenue streams. This will ensure that the lowest-cost VRE and storage can be effectively integrated into the grid, supporting efficient levels of oversizing required for FDRE projects and minimizing idle capacity in the system.
2. Better enforcement of RPOs and RCOs under the Energy Conservation Act, as envisaged in the Electricity Act, 2003 to further incentivize discoms to sign supply agreements.
3. Enforce air pollution controls on coal-fired power plants based on the polluter-pays principle or impose a carbon price on coal to reflect its societal costs. Alternatively, include socio-economic metrics in clean energy tender prices to provide a price premium to reflect reduced pollution compared to coal power.
4. Continue support for BESSs through VGF or by providing manufacturing incentives for promoting domestic manufacturing to drive down the costs of locally sourced panels.

Where FDRE is considered the most appropriate option, several policy options could maximize tender uptake:

1. Undertake confidential negotiations with discoms and developers on the barriers to accelerating FDRE uptake and the redesign FDRE tenders, such as
    - less onerous DFR requirements to reduce the amount of oversizing.
    - a capacity charge for battery storage that can provide system-wide services (such as ancillary services).
    - ensure penalties are sufficient to ensure the firmness of agreed DFRs to give procurers confidence in FDRE as a reliable source of power—for example, through
        i. penalty calibration linked to transparent benchmarks;
        ii. complementary mechanisms, such as insurance-like instruments that share risk more efficiently; or
        iii. clear safeguards against retrospective changes.
2. Shift to other support mechanisms for FDRE based on market prices, such as CfDs or a CIS.
3. Provide clear guidance to discoms on methodologies to compute short-term, medium-term, and long-term resource adequacy, and incentivize integrated resource planning at the state level through capacity-building initiatives
4. Create guidelines for technology-neutral capacity auctions where FDRE can compete directly against coal and other firm sources based on objective metrics, such as minimum availability, ramp rate, and ability to provide ancillary services.

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Appendix A. Compilation of FDRE Tenders in India

We identified firm and dispatchable renewable energy (FDRE) tenders issued between 2023 and 2025 by reviewing the information released by key tendering authorities, both at the Central and state levels, to the possible extent. Our analysis considered central tendering agencies, including Solar Energy Corporation of India (SECI), Satluj Jal Vidyut Nigam (SJVN) Limited, National Hydroelectric Power Corporation (NHPC) Limited, National Thermal Power Corporation (NTPC) Limited, state-level tendering authorities Rewa Ultra Mega Solar Ltd (RUMSL), Punjab State Power Corporation LTD (PSPCL), and private utilities, including Tata Power Distribution and Torrent Power. For each of these tenders, we documented the year of issue, capacity auctioned, FDRE technology configuration (peak guarantee, load-following, round the clock [RTC]), present status of the tender (Request for Selection [RfS] issued, under execution, tender awarded or cancelled), and the winning bid (Table A1).

Table A1. FDRE tenders issued between FY 2023–FY 2025

Issue Year	Tendering Authority	Capacity (MW)		Source
		Issued	Awarded	
2023	SJVN-FDRE-I	2368	2368	Tender details
	SECI-FDRE-I	500	500	Tender details
	SECI-FDRE-II	1500	1500	Tender details
	SECI-FDRE-III	800	800	Tender details
	SECI-FDRE-IV	1260	630	Tender details
	NHPC FDRE-I	1500	1400	Tender details
	RUMSL	400	400	Tender details
	NTPC FDRE-I	3000	1584	Tender details
	SECI-FDRE-V	1000	1000	Tender details
2024	NHPC FDRE-II	1200	1200	Tender details
	SJVN-FDRE-II	1200	1200	Tender details
	NTPC FDRE-II	1200	760	Tender details
	NHPC FDRE-III	1200	1200	Tender details
	SECI-FDRE-VI	2000	200	Tender details
	SJVN-FDRE-III	1200	480	Tender details
	NTPC FDRE-III	1200	1200	Tender details

Issue Year	Tendering Authority	Capacity (MW)		Source
		Issued	Awarded	
	SECI-RTC-IV	1200	420	Tender details
	PSPCL	1000	1000	Tender details
	SJVN-FDRE-IV	1500	1500	Tender details
2025	Tata Power D	250	250	Tender details
	Torrent P	200	200	Tender details

Source: Authors' compilation based on official FDRE tender documents.

Appendix B. Assumptions for Onshore Wind Levelized Cost of Electricity Estimation

For onshore wind, we adopted technology and cost parameters from the Central Electricity Authority's India Technology Catalogue (Central Energy Agency & Danish Energy Agency, 2022) and its embedded learning-curve framework. The catalogue applies a single-factor learning rate of 5% for onshore wind, combined with India-specific deployment projections. This yields a moderate capital expenditure (CapEx) decline of ~5%–15% by 2050 (2020=100 index of 86–93 by 2050).

For CapEx and operations and maintenance (O&M) costs (both fixed and variable), we directly map the catalogue's milestone years (2020, 2030, 2040, 2050) into our levelized cost of electricity (LCOE) model. For all the intervening years, we interpolate values using a compound annual growth rate approach to ensure smooth, realistic trajectories instead of abrupt step changes. This is essential to reflect gradual technology cost declines, which better align with market dynamics. After interpolation, we use the Financial Modelling of Offshore Wind model to estimate the LCOEs for onshore wind, based on the assumptions listed in Table B1. Since all our calculations for FDRE are anchored from 2025 onwards, for onshore wind as well, we consider 2025 LCOE values as the starting point.

Table B1. Assumptions used in our onshore wind LCOE estimation

Sl №	Topic	Our assumptions (based on the CEA Technology Catalogue)
1	**CapEx (2020 prices)** (INR crore/MW) (For all the intervening years, we interpolate the capex values using compound annual growth rate.)	**2020**: 6.66 **2030**: 6.24 **2040**: 6.04 **2050**: 5.91 (mid-range projection)[14]
2	Learning rate	5% (applied to CapEx)[15]
3	**O&M costs – Fixed** (INR crore/MW/year) (For all the intervening years, we interpolate the fixed O&M costs.)	**2020**: 0.068 **2030**: 0.077 **2040**: 0.087 **2050**: 0.097

[14] The CEA projects onshore wind CapEx in 2050 at **INR 5.7 crore–6.2 crore/MW**, depending on deployment, equivalent to a ~5%–14% drop from 2020. The CEA also cautions that while learning analyses typically reflect turbine CapEx (INR/MW), increases in turbine size and full-load hours mean the effective LCOE reduction can be larger than CapEx-only trends suggest—a point relevant for long-run firm and dispatchable renewable energy cost evolution.

[15] In this analysis, the learning rate for onshore wind reflects the expected percentage reduction in capital costs with each doubling of cumulative global wind capacity; these global cost reduction trends are then combined with India-specific deployment projections from the CEA technology catalogue to derive the capital cost assumptions used in our 2025 LCOE estimations.

Sl №	Topic	Our assumptions (based on the CEA Technology Catalogue)
4	**O&M costs – Variable** (INR crore/MW/year) (For all the intervening years, we interpolate the variable O&M costs.)	**2020**: 240 **2030**: 229 **2040**: 220 **2050**: 213
5	**Capacity utilization factor**	27%[16] (current all-India median; some states may reach even higher capacity utilization factor values, but we use 27% for modelling consistency)
6	**Technical lifetime**	27 years (balancing the 25 years (2020) to 30 years assumption (2030) in the CEA Technology Catalogue)
7	**Taxes and duties in LCOE**	Excluded in base LCOE (consistent with catalogue cost basis in 2020)
8	**Transmission costs**	Excluded from LCOE estimation

Source: Authors' compilation based on CEA & DEA, 2022.

[16] For the capacity utilization factor (CUF), we draw directly from the CEA FDRE document (2023), which reflects government benchmarks used for tender design. It reports annual CUFs for key wind-rich states: Gujarat (26.67%), Karnataka (30.61%), Maharashtra (26.83%), and Tamil Nadu (29.15%). For our modelling, we adopted a benchmark CUF of 27%, which is slightly conservative, but we use it deliberately to avoid overstating generation potential while remaining consistent with government benchmarks. These four states together account for over three quarters of India's installed wind capacity, making them a representative reference for national modelling.

Appendix C. Estimating Externalities of Thermal (Coal) Power

We derive India-specific estimates of mortality, morbidity, and carbon dioxide (CO_2) emissions attributable to pollution from thermal power plants (TPPs) using the most recent and relevant literature. We then applied social cost values to each mortality, morbidity, and CO_2 emissions outcome to quantify their economic impacts. Finally, we normalized the total social cost by the electricity generated from coal in FY 2025, yielding an estimate of the external cost per unit of electricity (kWh) produced from TPPs in India. In our assessment for externalities, we considered two scenarios: conservative (lower bound) and less-conservative (upper bound). We estimate the lower- and upper-bound values for each category–mortality, morbidity, and social cost of carbon, to provide the extent of impacts from coal TPPs.

1. **Mortality**: In India, between 164,000 and 197,500 premature deaths in 2025 are expected to be attributed to particulate matter ($PM_{2.5}$) emissions from coal-powered TPPs (Guttikunda & Jawahar, 2018). Viscusi and Masterman (2017) apply a global income-adjusted approach and estimate India's value of a statistical life (VSL) at **INR 1.78 crore (USD 0.275 million)** in 2017.[17] Another India-specific study estimates a significantly higher VSL figure for India, **INR 4.46 crore** (USD 0.63 million) in 2018 (Majumder & Madheswaran, 2018).

   For our assessment on mortality externalities for two scenarios (conservative and less conservative), we attributed 164,000 deaths under conservative and 197,500 premature deaths under less conservative scenario. Similarly, we used the VSL of USD 0.275 million for the conservative scenario and USD 0.64 million for the less conservative scenario. To ensure comparability, we adjusted VSL values for inflation to reflect its equivalent net present value in 2025, resulting in **USD 0.36 million** and **USD 63 million** for the conservative and less-conservative scenarios, respectively. Using these values, we estimated the mortality-related externalities under the two scenarios.

   Multiplying the lower-bound estimate of 164,000 premature deaths by USD 0.36 million, we arrived at a total mortality-related cost of approximately USD 59.14 billion. Dividing this by total coal-based electricity generation in FY 2024/2025 (1,363 billion units), we calculated an external cost of **INR 3.69 per kWh**, which represents the conservative estimate for the mortality-related economic burden of coal power (Table C1).

   Similarly, for estimating the less-conservative scenario, we multiplied the upper-bound estimate of 197,500 premature deaths by USD 63 million to arrive at the total mortality-related cost of **INR 12,48,653.12 crore**. Using the total coal-based electricity generated in FY 2024/2025 (1,363 billion units), we estimated the

[17] The Organisation for Economic Co-operation and Development defines VSL as the monetary value to avoid the risk of mortality. VSL is estimated for various countries using benefit-transfer method supported by meta-analysis and quantile regression. The VSL value for India is also estimated using India's income level and risk potential.

mortality-related economic burden of coal power of INR 9.16/kWh for a less-conservative scenario (see Table C1).

2. **Morbidity**: Air pollution in India causes the loss of approximately 1.3 billion working days annually (Gupta et al., 2021). TPPs account for about 9% of the population-weighted ambient $PM_{2.5}$ in India (Cropper et al., 2021). Assuming uniform distribution, we attribute **117 million** (9% of 1.3 billion) lost workdays per year to emissions from TPPs for both the conservative and less-conservative scenarios. *The Economic Survey 2024-25* (Ministry of Finance, 2025) reports a daily wage rate of INR 418 for casual labourers and INR 690 for regular workers. In our assessment, we attribute the daily wage rate for casual labour (INR 418) under the conservative scenario and regular workers (INR 690) under less-conservative scenario.

   For the conservative scenario, we multiplied the annual lost working days (117 million) by the average daily wage rate for casual labour (INR 418) to arrive at the total morbidity cost of **INR 4,890.6 crore**. Dividing this by total coal-based electricity generation in FY 2024/2025 (1,363 billion units), we calculated the morbidity-related external cost of coal power at **INR 0.04 per kWh** under the conservative scenario (Table C1).

   Conversely, for the less-conservative scenario, we estimated the morbidity cost by multiplying the 177 million annual lost working days by the average wage of a regular worker (INR 690), resulting in **INR 8,073 crore**. Dividing this by the total coal-based electricity generation in FY 2024/2025, we calculated the morbidity-related external cost of coal power at **INR 0.06 per kWh** under the less-conservative scenario.

3. **CO_2 emissions**: According to the Government of India (Press Information Bureau, 2024a), between FY 2019 and FY 2023, CO_2 emissions rose from 897.28 million tonnes to 943.04 million tonnes. During the same time period, India's generation from thermal power also rose from 987.68 billion units to 1043.83 billion However, due to a lack of data on CO_2 emissions for FY 2025, we estimated CO_2 emissions for FY 2025 at **1,231 million tonnes of CO_2 equivalent** (tCO_2e) using carbon intensity derived from historical emissions and coal-based electricity generation. Ricke et al. (2018) follow a modular, empirically driven integrated assessment approach focusing on uncertainty quantification across climate, socio-economic, damage, and discounting modules in estimating India-specific values for the social cost of carbon (SCC). The SCC for India was estimated at between USD 49/tCO_2e and USD 157/tCO_2e. We used the annual inflation rate (4.95%) to adjust the reference value in FY 2018 to reflect their equivalent net present value in 2025. (EZTax India, 2024). The adjusted SCC values for conservative and less-conservative scenarios are **USD 62.7/tCO_2e** and **USD 200.9/tCO_2e**, respectively.

   In estimating the SCC for the conservative scenario, we multiplied the total CO_2 emissions from coal-based electricity generation (1,231 million tonnes) by USD 62.7/tCO_2e, resulting in a total SCC of **USD 77.2 billion**. Dividing this by coal-based electricity generation (1,363 billion units), we estimated the CO_2 externality from coal-based electricity generation to be **INR 4.81 per kWh**.

Conversely, in the less-conservative scenario, applying the upper-bound carbon price of USD 200.9 per tonne equivalent CO_2, we estimated a total SCC of **USD 274.3 billion**. Dividing this by coal-based electricity generation, we estimated the externality cost of CO_2 at **INR 15.4 per kWh** under the less-conservative scenario (Table C1).

Table C1. Social cost of externalities

		Number that could be attributed to pollution from TPPs **(A)**	**Value assigned to per unit** **(B)**	**Overall economic impact** **(C = AxB)**	**Electricity generated in India using TPPs (in billion units) in FY 2025** **(D)**	**Monetized health impacts – conservative (in USD or INR/kWh)** **(E = C/D)**
Mortality (number of deaths)	Conservative	1,64,000 (year 2025)	USD 275,000 (USD 2017) USD 360,651 (USD 2025) (Average inflation rate increase – 3.58% per year (CPI Inflation Calculator, 2025)	USD 59.14 billion (USD 2025)	1,363	USD 0.04 INR 3.69
	Less conservative	1,97,500 (year 2025)	INR 4.46 crore (INR 2018) INR 6.32 crore (INR 2025) (Average inflation rate increase – 4.95% per year (EZTax India, 2024)	INR 12,48,653.12 crore		INR 9.16

Morbidity (no. of working days lost)	Conservative	11,70,00,000 (TPPs contribute 9% of the $PM_{2.5}$ in India, and a total of 1.3 billion working days are lost per year in India due to health problems caused by $PM_{2.5}$)	INR 418 per day for casual workers (Ministry of Finance, 2025)	INR 4,890.6 crore	1,363	INR 0.04
	Less conservative		INR 655 per day for casual workers (Ministry of Finance, 2025)	INR 8,073 crore		INR 0.06
CO_2 emissions (social cost of CO_2)	Conservative	1231.4 million tonnes of CO_2 (year 2024) (India's carbon intensity for coal power is 900 grams of CO_2 per kWh of electricity produced. In FY 2025, India produced 1363 BU of electricity from thermal power.)	USD 49/tCO_2 (USD 2018) USD 62.7/tCO_2e (USD 2025) (Average inflation rate increase – 3.58% per year) (CPI Inflation Calculator, 2025)	USD 77.2 billion	1,363	USD 0.06 INR 4.81
	Less conservative		USD 157/tCO_2e (USD 2017) USD 200.9 (USD 2025) (Average inflation rate increase – 3.58% per year)	USD 247.3 billion		USD 0.18 INR 15.43

Note: Methane emissions are excluded from the above analysis, as they are primarily emitted in the coal mining process (upstream value chain) and are beyond the scope of this analysis.

Source: Authors' compilation based on Guttikunda & Jawahar, 2018; Ministry of Finance, 2025; Press Information Bureau, 2024a; Ricke et al., 2018).

Appendix D. Methodology for Estimating Jobs From Firm and Dispatchable Renewable Energy

We estimated employment impacts from firm and dispatchable renewable energy (FDRE) using India-specific and technology-specific job coefficients. Job coefficients, expressed as job-year per megawatt (MW), capture the average labour requirements associated with construction, pre-commissioning, and operations and maintenance phases. This study restricts employment impacts to jobs created from construction, pre-commissioning, operations, and maintenance (Table D1).

Kuldeep et al. (2017) estimated job-year per MW of solar and wind by conducting detailed surveys across project phases, including manufacturing, operations and maintenance, business development, and design and pre-construction. Another study by CEEW (2025) estimates the employment coefficient for battery energy storage from a survey with key players in battery manufacturing.

FDRE projects typically combine solar, wind, and storage technologies. To calculate the jobs associated with each of these individual technologies, we allocated the awarded FDRE capacity into its technology components (as per the generation ratio calculated from different combinations of FDRE, as highlighted in the *India Technology Catalogue* [Central Electricity Agency & Danish Electricity Agency, 2022]). Each of these components is multiplied by the corresponding job coefficients to obtain the employment effect for that technology. The total number of jobs created is calculated as the sum of solar, wind, and storage employment.

Table D1. Job coefficients for solar, wind, and battery storage technologies

	Construction and pre-commission (job-year per MW)	Operations and maintenance (job-year per MW)
Solar	2.7	0.5
Wind	0.6	0.5
Battery Energy Storage	3.12	0.4

Source: Kuldeep et al., 2017; CEEW, 2025.

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