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An Assessment of India's Energy Choices: Managing India's Renewable Energy Integration through Flexibility

Vivek Sen, Climate Policy Initiative
Saurabh Trivedi, Climate Policy Initiative
Gireesh Shrimali, Climate Policy Initiative

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Descriptors

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Contact	Dr. Gireesh Shrimali	gireesh.shrimali@cpidelhi.org

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Executive Summary

India has ambitious targets for addressing energy access needs as well as climate change. These priorities will result in a significant share of power in India generated by renewable energy. The Government of India plans to install 175 GW of renewable energy projects by 2022 and 275 GW by 2027. This means that renewable energy generation will contribute about 20.3% and 24.2% of the total electricity requirement in 2021-22 and 2026-27, respectively.

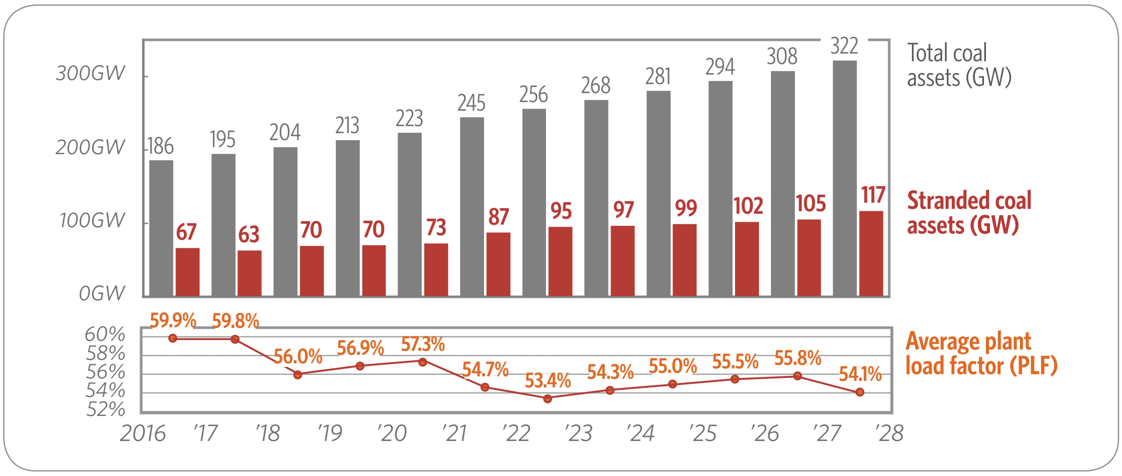
In meeting these goals, however, the Indian power sector faces twin challenges:

1. **Managing renewable energy will require increased flexibility in the system.** Renewable energy generation fluctuates predictably and unpredictably whenever the sun isn't shining or the wind isn't blowing, making short-to-mid-term operations of maintaining a steady energy flow from a grid to customers challenging. Further, seasonal variability of renewables makes long-term planning difficult. As renewable energy increasingly penetrates the Indian grid, a portfolio of flexible, cost-effective back-up energy options will be required to meet five types of flexibility needs: Spinning and short-term reserves, load following, ramping, daily balancing, and seasonal balancing. Preliminary estimates indicate that approximately 5% of installed generation capacity will be required as flexible resources.
2. **There will be under-utilization of existing coal-based plants stressing the economics of the overall power sector.** Most coal-based units in India in 2017 are operating at an average plant load factor (PLF) of ~61%; this may fall to ~50% by 2022 (Figure ES-1). Since a coal plant becomes economically unviable (i.e. stranded) at a PLF of 52%, at least 1/3rd of the installed coal capacity is likely to be stranded during 2017-2027,[1] presenting potentially negative impacts on India's overall economy as investors in these assets are left with unviable investments.

This paper is part of a series of studies led by Climate Policy Initiative for Shakti Sustainable Energy Foundation that looks at paths to renewable energy penetration in India along different dimensions including the social costs, macroeconomic impacts, environmental impacts, financial risk, and flexibility considerations. This component specifically looks at the plausibility of using existing coal-based power plants as flexibility reserves.

In the short-term, we find that transitioning existing coal power into flexible coal power is a cost-effective solution for increasing renewable energy penetration and addressing potential stranded asset risk in the broader Indian energy system.

Figure ES-1: Stranded coal assets compared to total coal assets. (CPI Analysis)



1 We have considered that the 72 GW identified by Central Electricity Authority for retirement due to ineligibility to conform to environmental norms are not retired as planned

Our analysis shows that:

- **Shifting existing coal-based power for flexibility is technically feasible.** Pilot cases in Germany and the USA show that making existing coal-based power plants flexible is technically feasible.
- **This path has positive benefits for India's climate and energy goals – it will reduce emissions compared with a business-as-usual scenario.** Our analysis shows that converting a baseload coal plant to a flexible plant can save CO_2 emissions of approximately 0.11 million tons/MW due to the reduction in the average load factor from normative levels of 85% to desired levels of 40%, and also due to the expected reduction in the project life from 40 years to 35 years.
- **Flexible coal may be the most cost-effective flexible solution in the near-term.** Our analysis compared flexible coal to several other flexibility options. The upfront investment costs of lithium ion batteries and pumped hydro are 500-2000% and 400-1800% more than the incremental cost required for making a coal plant flexible, respectively. If the stranded cost of coal plants is taken into account this difference will increase further.

We emphasize that we are not recommending that flexible coal is a long-term solution. In fact, our analysis shows that it is important that the cost of cleaner flexibility options, such as batteries, come down as soon as possible so that India can transition to a low-carbon electricity system in an accelerated manner. So, assuming that this pathway is taken as a short-term solution, our analysis reveals several important considerations for policy makers and investors to ensure it is implemented as cost-effectively as possible.

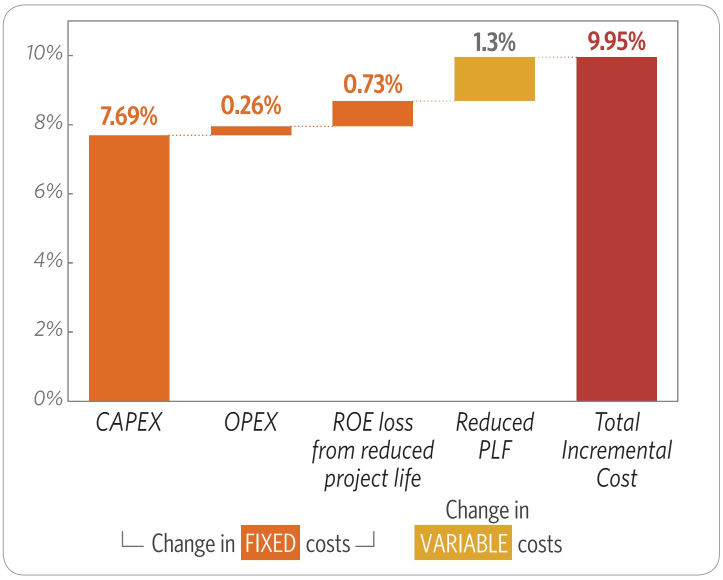
First, converting existing coal plants into flexible plants will require compensation to owners of these assets to remain economically viable. The additional costs include: incremental fixed costs due to capital expenditure for retrofits, incremental operating expenses for technical upgrades and maintenance, incremental variable costs due to lower PLFs, and loss in return on equity due to the reduced plant life.

However, the additional cost of converting a coal plant into a flexible plant is low-moderate; the additional cost would be only 5%-10% of the total project cost of baseload coal plant in net present value terms (INR/MW) or 8%-22% in levelized terms. These are indicative costs based on scenarios accounting for the year of flexibility implementation, the lifetime of flexible plant, PLF levels, and the capital expenditure for flexibility. Figure ES-2 provides indicative upper level incremental costs.

Flexible coal should be procured cost-effectively using appropriate market mechanisms, such as capacity auctions. A market-based mechanism, such as auctions, may be the most cost-effective way for procuring flexibility, while also ensuring that flexible coal plants get adequate compensation. While we provide some insight into these auctions, detailed design would be part of future work.

While we have provided preliminary insights into managing the twin issues of managing high levels of renewable energy and potential asset stranding of coal plants, more work needs to be done along two fronts to move this potential solution forward: 1. It will be important to do more intensive research to ensure that benchmark costs for compensating flexible coal plants are appropriately calculated; 2. As noted, appropriate market-based mechanisms will need to be deployed to procure flexibility cost-effectively, and these require additional research, design, and feasibility assessments.

Figure ES-2: Indicative upper bound incremental cost in NPV terms of converting a baseload coal plant into a flexible plant (CPI Analysis)



Contents

1. India is on a path to developing a low-carbon electricity system

India has embarked on a transition to a low carbon economy and, as part of this, renewable energy may constitute as much as ~44% of the installed capacity mix by 2027.

The power sector in India traditionally has been heavily dependent on fossil fuels (mainly, coal, lignite, gas and diesel). In 2017, coal-fired power plants constituted 58% of the installed generation capacity and 75% of generation (CEA, 2017).

As part of its Nationally Determined Contribution (NDC) submitted to the Paris Climate Agreement, India has committed to providing 40% non-fossil fuel electricity capacity, as well as to reducing emission intensity by 30-35% by 2030. As an intermediate target, India plans to add 175 GW of renewable energy by 2022 which includes 100 GW of solar, 60 GW of wind, 10 GW of biomass and 5 GW of small hydro. By 2027 the total renewable energy installed capacity is expected to reach 275 GW (Figure 1.1).

Due to India's renewable push via a variety of policy mechanisms, at the end of 2017 the installed capacity of wind and solar stood at 30 GW and 16 GW, respectively. While renewable energy deployment may not quite reach India's ambitious targets for 2030, the share of renewable energy in India's power mix is expected to increase significantly over the coming years, from 9% in 2017 to 23% in 2027 (Figure 1.2).

This study is structured as follows. Section 2 discusses the twin challenges of India's renewable electricity transition: managing flexibility and combating potential stranded assets resulting from reduced use of coal-based power generation. Section 3 then proposes flexible coal-based power plants as a solution to the problems discussed in Section 2 including how this would work and its economics. Section 4 discusses market design requirements for enabling development of flexible coal-based power plants. Section 5 concludes the report and discusses future work needed.

Figure 1.1: Renewable energy capacity addition

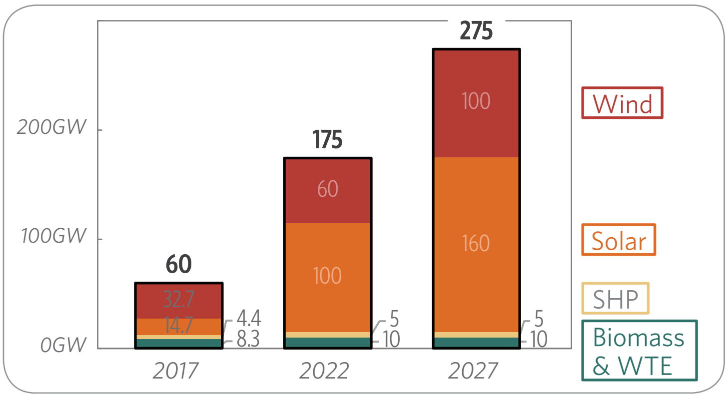
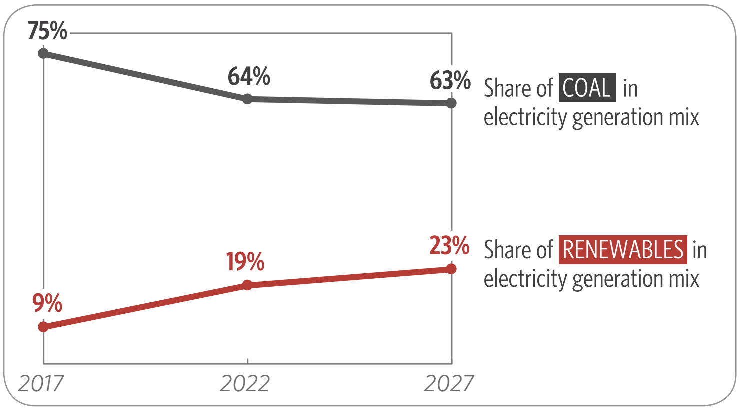


Figure 1.2: Share of renewables in the electricity generation mix



2. Twin challenges: Managing both flexible grid operations and reduced plant load factors for coal-based power plants

As renewable energy increases within India's energy mix, the Indian power system faces two key challenges:

(a) Managing grid flexibility requirements through operational reserves

(b) Managing potential stranding of coal-based assets given decreasing plant load factors (PLFs)

We discuss each of these challenges in the subsequent sub-sections.

2.1 Managing grid flexibility requirements through operational reserves

The aggregate impacts of integration of variable renewable energy on the grid suggests the need for having requisite flexibility to have seamless grid operations. The flexibility requirements are met by having reserve capacity available to the system operator that are used to manage grid operations in cases of disruptions like power imbalances.

Various types of operational reserves differentiated by response time are needed to meet the flexibility requirements in the grid.

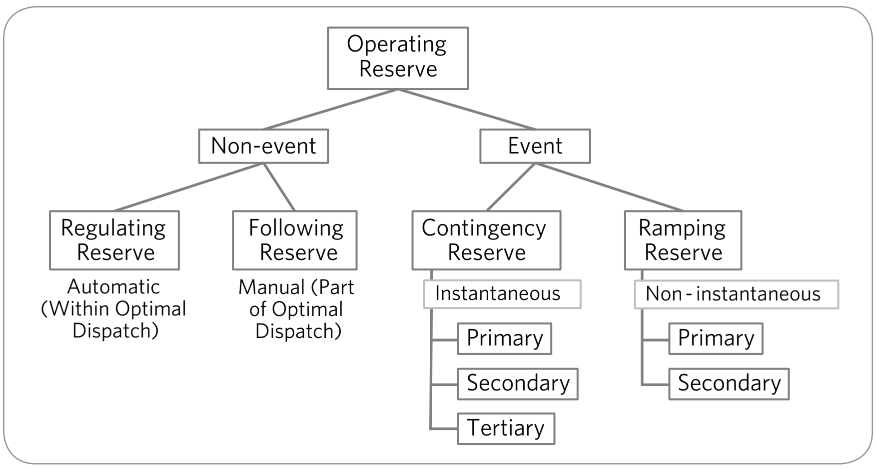
An "operating reserve" is defined as any type of generation capacity being used to support active power balance between supply and demand. Operating reserves can be further divided into non-event reserves and event reserves (Figure 2.1).

Event reserves are for active power balancing during infrequent events that are more severe than imbalances encountered during normal conditions, such as generation outages. Non-event based reserves are for active power balancing during normal conditions (Table 2.1), such as regular fluctuations in energy supply and demand that occur throughout the course of a day or year.

The increasing share of variable renewable generation in the grid makes grid operations more complex and more difficult to manage.

The increasing share of variable renewable generation in the grid makes grid operation more complex and more difficult to manage. For instance, in India, peak electricity demand is from 6-7 pm, when solar generation is unavailable and wind generation has not picked up. Renewable energy generation also fluctuates multiple times during the day, regularly requiring the grid operator to adjust its day-ahead, hour-ahead, and real-time operations. Additionally, it is difficult for the grid operator to predict and schedule generation sources to account for seasonal variation in renewable energy generation, making long-term planning difficult.

Figure 2.1: Types of operating reserves



Source: NREL, 2011

Renewable energy generation can thus lead to higher flexibility needs due to steeper ramps, deeper turn downs, and shorter peaks in system operations. This accentuates the need for flexibility in the grid by adequate amounts of both event based and non-event based reserves. Establishing event reserves requires system-level simulations; and, this is likely to be established using more detailed studies such as (ongoing) the Energy Transitions Commission (ETC) project. In order to provide preliminary insights, however, using the net load methodology (see Box 2.1, p. 10), we have established representative non-event reserves, comprised of following reserves and regulating reserves as in the following subsections.

2.1.1 FOLLOWING RESERVES:

Load following is essentially the action to follow the trending load pattern within the day. This is usually performed by economic dispatch, and sometimes involves the starting and stopping of quick-start generation facilities. These are reserve requirements that will occur on any typical day of operation in an electricity grid, and are typically represented as the (maximum) ramping up/down of generating capacity in the particular time.

We find that the ramping up requirements would rise from 13.27 GW in 2017 to 75.05 GW in 2027.

We have plotted the typical load curves for 2017, 2022 and 2027 (Figure 2.2). We established the ramp up and ramp down rates required for meeting the system load using the net load method.

The largest ramping requirement is seen in the evening time during 5 to 7pm, primarily due to reduction in solar generation. This brings the need of ramping up power generation from other generating sources. This ramping up is generally provided by coal fired power stations as India is predominantly reliant on coal-based capacity -- ~58% of electricity generation in 2017 is from coal-based power generation (CEA, 2017).

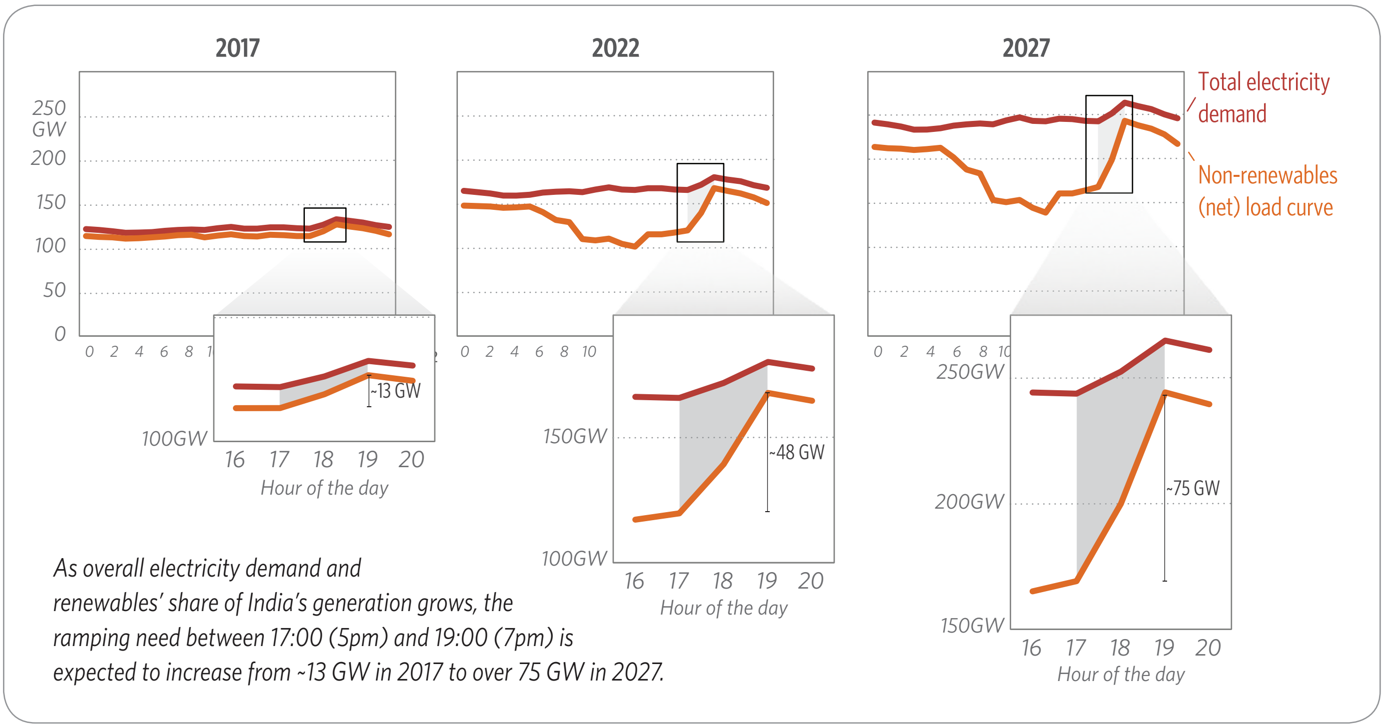
We find that, with ~60 GW of renewable energy installed capacity in 2017, the ramping up requirement is ~13.27 GW during 5 to 7pm. By 2022, with 175 GW of renewable energy in the energy mix, this would increase to 48.12 GW. By 2027, with 275 GW of renewable energy capacity, this would further increase to 75.05 GW in 2027.

Table 2.1: Categorization of non-event and event based operating reserves

Non-event Reserve	Capacity available for active power balancing during normal conditions, or those that occur continuously.
Regulating Reserve	Random capacity that is used during normal conditions for assistance in active power balance to correct the current imbalance. Requires automatic, centralized response and is faster than economic dispatch optimization used to meet imbalances.
Following Reserve	Capacity used during normal conditions for assistance in active power balance to correct future anticipated imbalances. Does not require automatic, centralized response and is slower than economic dispatch optimization.
Event Reserve	**Capacity available for active power balancing during infrequent events that are more severe than during normal conditions.**
Contingency Reserve	Capacity available for correcting instantaneous imbalances by providing assistance in active power balance during infrequent events beyond the normal conditions.
Ramping Reserve	Capacity available for correcting non-instantaneous imbalances by providing assistance in active power balance during infrequent events beyond the normal conditions.
Primary Reserve - Contingency	Part of the Contingency Reserve that automatically responds to instantaneous active power imbalance to stabilize the system frequency to the normal operating range.
Secondary Reserve - Contingency	Segment of the Contingency Reserve that is not automatically responsive to the instantaneous active power imbalance and corrects frequency to nominal and/or Area Control Error (ACE) to 0.
Tertiary Reserve - Tertiary Reserve	Part of the Contingency Reserve that is accessible for help with supplanting Primary and Secondary Reserve. Utilized amid a severe instantaneous event so that Primary and Secondary reserves are available for subsequent instantaneous events.
Secondary Reserve - Ramping	Part of the Ramping Reserve that is used to correct the imbalance of a severe non-instantaneous event and corrects the frequency to nominal and/or ACE to 0.
Tertiary Reserve - Ramping	Part of the Ramping Reserve that is available for assistance in replacing the Secondary Reserve used during a severe non-instantaneous event so that eventually Secondary Reserves are available for subsequent events.

Source: NREL, 2011

Figure 2.2: Net load curve for the year 2017, 2022 and 2027



Source: CPI Analysis

We find that existing coal plants in the Indian grid can adequately handle the ramping up requirements of 391 MW/min in 2027.

In the Indian grid, the ramping up requirement would largely need to be met by coal generation. In 2027, coal-based generation would be almost ~63% of our energy generation mix, meaning that almost 47 GW (63% of the total ramping up requirement of 75 GW) would have to be supplied through coal-based power. The average ramping up required would be 391 MW/min (= 47 GW*1000/60*2)

This 47 GW of ramping up capacity would have to come from 321 GW of coal capacity installed in 2027, by taking these plants from the expected PLF of 54% to the maximum PLF of 85%. That is, the capacity available for ramping up would be 99.08 GW (= 321 GW*(85%-54%)). Given the average ramping up rate for a coal-based power plant as ~2.75% (Agora, 2017), this which results in total ramping up capacity of 2736 MW/min (= 99.08 GW*2.75%*1000), which is more than enough for the required 391 MW/min.

Box 2.1 Net Load Methodology (CERC, 2015)

"Net-load" represents the demand that must be supplied by the conventional generation fleet if all of the (inflexible) renewable energy is utilized. We have analyzed the non-event based reserve requirements; namely following and regulating reserves using the net load method. The following reserves are simply derived from the slopes of the net-load curves; whereas the regulating reserves are derived from the statistical properties (in particular, standard-deviation) of the underlying net load curves at appropriate time intervals, namely hourly basis (for tertiary reserves), 5-minute basis or 15-minutes (for secondary reserves).

Thus, in 2027, the available ramping rate of 2,736 MW/min can be achieved if all of the available ramping capacity of 99.08 GW is ramped up simultaneously from 54% to 85% PLF. The grid would, therefore, require coal plants specifically meant to deal with the ramping requirements.

2.1.2 REGULATING RESERVES:

Regulating reserves are needed for fast balancing requirements to manage random variations in load or generation; and are provided by centralized control centers. The accuracy of the load and renewable energy generation forecasts has a significant effect on the calculation of system reserve levels as renewable energy introduces greater uncertainty on the system. Using the net load methodology (Box 2.1) we have computed the upper bounds of regulating reserve requirements for the year 2017 and for year 2022 and 2027 on projected data in Table 2.2.

Table 2.2: Regulating reserve requirements in 2017, 2022, and 2027

	2017	2022	2027
Regulating reserve (MW)	7,396.14	27,354.00	43,001.97

Source: CPI Analysis

2.1.3 OPTIONS FOR MANAGING GRID FLEXIBILITY REQUIREMENTS

In India, in the short-to-medium term, typical balancing options may not be available, requiring exploration of flexible coal as a viable option.

As shown in the previous sections, as renewable energy penetration is increasing, the demand for flexibility in the system is also increasing. Power Grid Corporation of India, in July 2012, strongly recommended that, apart from the initiatives like strengthening and enlarging the transmission network, more flexibility should be built into the generation portfolio (PGCIL, 2012)[2] in its report.

The available technology options to manage the first challenge of grid operations in a high renewable energy penetration scenario are:

1. Greater connectivity between regions
2. Balancing capacity, through, potentially, a combination of:
    a. Large (storage based) hydro power plants
    b. Combined cycle gas turbines
    c. Adequate spinning reserves
    d. Lithium-ion storage batteries
    e. Flexible coal power plants

One option to manage seamless grid operations that have high renewable energy penetration is by having inter-regional connectivity. This would allow the excess power from one region to be transferred to another region when needed. However developing inter-regional transmission capacity is an expensive option. Further, weak following sub-transmission and distribution networks limit the usefulness of this option.

Another option would be balancing capacity that can be quickly ramped up and down so that the imbalances can be met locally or within the region. Options there include large storage based hydro power plants and combined cycle gas turbines. However, considering the limited availability of gas generation[3,4,5] as well as hydro storage systems, grid balancing will be difficult to manage, unless the flexible coal option is explored. Comparisons are the different flexibility options are discussed more in Section 3.3.3.

2 PGCIL report Transmission Plan for Envisaged Renewable Capacity, July 2012
3 https://ippai.org/powernewsdetails/narendra-modi-govt-s-target-of-20-gas-energy-mix-by-2025-set-to-hit-high-cost-hurdle
4 http://www.thehindubusinessline.com/economy/plf-of-gasfired-power-plants-likely-to-decline-further-indra/article9901660.ece
5 IESS 2047, Energy Scenarios by NITI Aayog

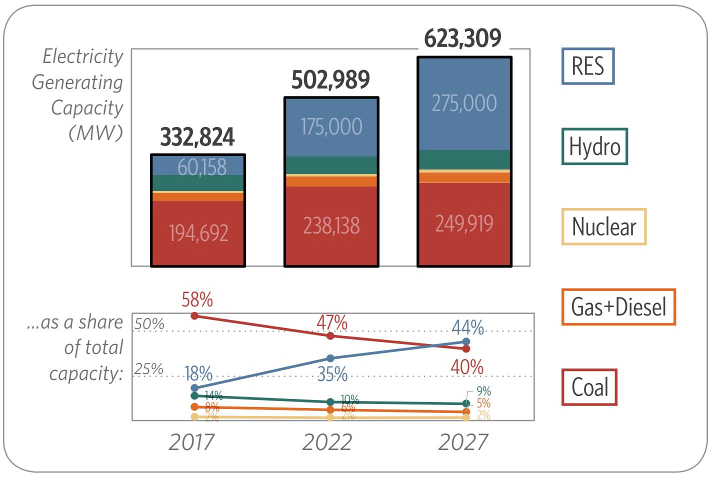
2.2 Managing potential stranding of coal-based assets given decreasing plant load factors

Indian coal-based plants must not only overcome underutilization of existing assets but also stricter environmental norms.

The power system in India has been heavily reliant on coal-based generation with coal contributing to as much as 75% of the generation mix in 2017 (CEA, 2017). However, coal-based power plants are facing problems such as significant underutilization of capacity and stringent environmental regulation compliance. In particular, the latter has resulted in CEA contemplating retirement of coal plants (See Box 2.2).

In terms of capacity underutilization, it is useful to examine the average PLF of coal plants over time, starting with current coal capacities. As per CEA, the current coal and lignite based generation capacity stands at ~194GW and is expected to grow 4.05% during 2017-18 (CEA 2017). Another ~50 GW of coal-based capacity

Figure 2.3: Likely installed capacity in 2017, 2022, and 2027



Source: CPI Analysis

is already under various stages of development that is expected to come online by 2022 (Figure 2.3).

Coal plants in India are incentivized (and designed) to run at an average plant load factor (PLF) of 85%, However, the average PLF of coal-based power plants has decreased from 78.9%[6] in 2007-08 to 62% in 2015-16[7] (Figure 2.4). Today (in 2017/2018), coal plants are operating at an average PLF of ~61%. CEA has also estimated that all coal-based thermal power plants may see a drastic fall in capacity utilization to as low as ~50% by 2022 as additional non-thermal electricity generation

Box 2.2: Retirement of 72GW proposed by CEA on account of non-conformance to environmental norms

Environmental norms are likely to provide a stronger basis for the Ministry of Power's plans to close older units. CEA has preliminarily identified 72GW of thermal generation capacity that cannot meet the revised SOx norms and would therefore be shut down. This 72GW represents 25-30% of India's installed conventional generation capacity.

~36GW of the 72GW capacity is less than 20 years old, meaning these plants have not recovered their regulated capital cost. Closing these plants could have direct commercial implications. Some of these plants have been commissioned in the last one-three years. Nevertheless, ~29GW of the capacity is more than 25 years old, and can be safely retired. This would increase to ~33GW by FY20, with ~13GW of NTPC plants.

In our analysis, however, we have considered that all of the 72GW identified will be retired. If these 72 GW assets are retired the resultant coal based capacity in 2027 would be ~250GW and the operating PLF would be in the range of 70% on average.

6 https://www.livemint.com/Industry/5vduPwYwJAKM4LPk458n0K/Falling-capacity-utilization-forces-Indias-coal-fuelled-pro.html

7 Several attempts to explain the trend of falling PLF have been made including: inadequate coal supply resulting in lower average dispatch; lack of inter-state and inter-regional transmission constraints that prevent free flow of power; loss-making distribution companies (DISCOMs) are reluctant to procure more power due to poor cost-realization from the consumers, and would prefer to resort to load-shedding instead; demand not exactly following the generation growth and growth in renewable energy generation.

capacities come online. This can result in many coal-based plants becoming economically unviable, a phenomenon known as "stranding."

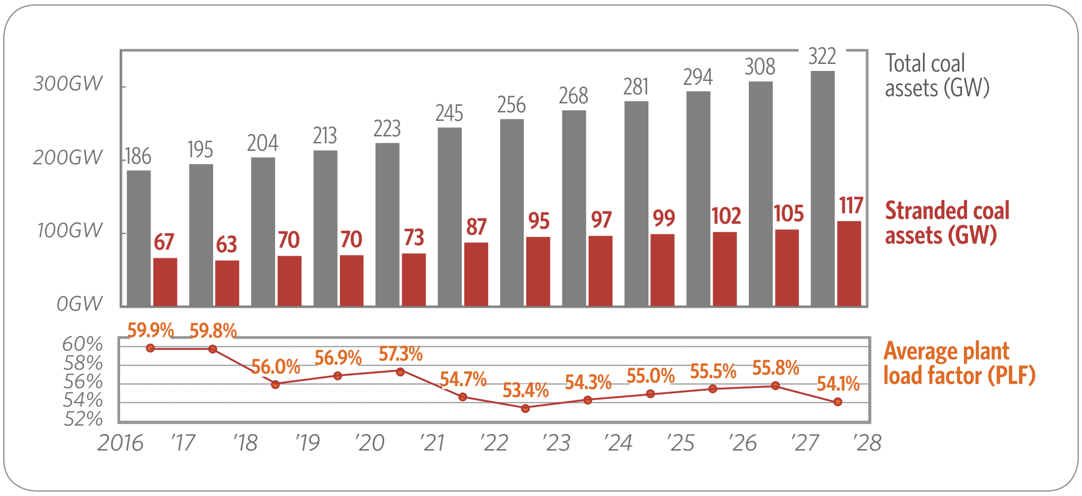
While transitioning away from coal is necessary for a sustainable future, stranded asset risk could negatively affect the overall power sector and renewable energy penetration. Even after accounting for CEA's planned retirement of 72 GW of coal capacity, we expect approximately 95 GW of coal capacity to be stranded in 2022.

To understand the impact of underutilization on financial performance of coal-based generating plants, we have compared the project internal rate of return (PIRR) with the weighted average cost of capital (WACC), where WACC is the expected average cost of funds from both debt and equity sources and PIRR is the expected return. A project is considered economically viable when the PIRR is greater than or equal to the WACC; and economically unviable otherwise.

Using normative parameters for coal-based generation plants in India,[8] we find that at a PLF of 52% the PIRR is equal to the WACC, and the PIRR falls below the WACC at PLFs below 52%. As many coal plants are/would-be operating below a PLF of 52%, these plants are likely to be economically unviable or stranded. We find that approx. 95 GW of coal capacity would be in stranded in 2022 (see Box 2.3). In case we consider progressive retirement of 72 GW of coal-based capacity starting from year 2021 (retirement of 18GW in 2021), even then the stranded capacity is expected to be at ~77 GW in year 2022.

If this situation persists for a long time, this may result in these coal plants going out of business (see Box 2.4 for an estimate of plant level losses). In isolation, this would help avoid the most dangerous effects of climate change. However, in the current Indian political context, there may be increased political pressure to keep these plants alive at the expense of decreasing renewable energy penetration, given that most of these plants received investment based on policy certainty (Subramanian, 2017). This indicates that, in order to ensure that India continues to make progress towards its ambitious renewable energy targets, it would be appropriate to explore options for mitigating stranded asset risk.

Figure 2.4: Stranded coal assets compared to total coal assets



Source: CPI Analysis

8 Model worked out using normative PLF

Box 2.3: Expected coal capacity getting stranded in 2022

The coal based capacity addition during 2011 to 2017 was at a CAGR of 10.16%. Based on this CAGR the expected capacity is ~245 GW in 2022. We then used a CAGR of 5% which is half of the CAGR we had seen in the earlier period 2011-2017 (considering more emphasis on adding capacity through renewables rather than coal) to arrive at expected capacity by 2027 of 332GW and the operating PLF would be in the range of 52% on average. This comprises the 50 GW plants under construction as well. In this scenario, the expected stranded coal based capacity in 2022 would be ~95GW.

Further, when, we consider that all of the 72GW is retired progressively starting from 2021, then the resultant coal based capacity in 2027 would be ~250GW and the operating PLF would be in the range of 70% on average. With progressive retirement of 72GW of coal based capacity starting from 2021 (retirement of 18GW in 2021), the stranded coal based capacity is expected to be at ~77GW in 2022.

Box 2.4: Indicative cost of a stranded coal plant

In this paper, we focus on the cost implication of stranded coal plants only at the plant level and not on the financial system level. The stranded cost estimated here is to provide a sense of the sunk investment cost including expected return on investment that no longer would be recovered by the project developers.

Using a typical cashflow model for a general coal plant, the stranded cost of a coal plant would depend on the year when the plant gets stranded. If the plant gets stranded in its 15/30th year of project life then this stranded cost will be 43/35% of the initial capital expenditure. In levelized cost terms, the stranded cost will be ~INR 0.45/kWh every year until the actual expected life of the project.

3. Flexible coal as a short-term solution

Coal plants, if converted into flexible plants, can meet the flexibility needs of renewable power integration into the grid and can also help resolve the issue of stranding of coal plants.

Coal power can provide a short-term solution to both flexibility challenges and stranded asset risk until there are more feasible and cost effective solutions.

However, it is not a straightforward task to convert existing baseload coal plants into flexible plants due to several factors: investment requirements for upgrades, policy environment specific to flexibility issues, incentive mechanisms, availability and accessibility of suitable technologies, man-power skills, etc. Given the limited scope of the study, this section focuses mainly on the investment requirements for converting coal plants into flexible plants, with brief coverage of other issues. We also perform a high-level comparison between investments required to convert a baseload plant into a technically flexible plant, and investment required to use other cleaner technologies, which can be used as flexible reserves. Finally, we assess the impact of flexible coal plants on carbon emissions as well as renewable energy curtailment.

3.1 Previous research and experience

Extensive research has been undertaken on the options available to provide flexible power to the grid in high renewable energy penetration scenarios, and to understand the cost of managing flexibility. All these studies have independently focused on different aspects of renewable energy integration; importantly many of these reports have discussed the option of using coal plants to meet flexibility requirements. Below we provide a summary of this body of work.

- CPI (2017), a high-level, global study, discusses the path to low-carbon, low-cost electricity grids while investigating options to meet flexibility requirements; it establishes that operating existing fossil plants more flexibly can be used for providing flexibility to the grid.
- GIZ (2014), another high-level study, assesses interventions to increase balancing capability in renewable energy-rich states in India; qualitatively evaluates many options as short-term, medium-term, and long-term solutions; and establishes that providing flexibility through retro-fitting existing power plants is a costly but high impact solution.
- NREL (2017), a system-level simulation-based study of India, finds that increasing the flexibility of coal plants can help improve the ability of the system to efficiently integrate renewable energy. It also finds that relaxing the constraint on coal plant minimum generation levels has a greater impact on reducing renewable energy curtailment than increasing coal ramp capability and other aspects of coal flexibility. These improvements to minimum generation levels reduce operating costs, whether operational coordination is at the state or the regional level. Finally, it finds that retiring the least efficient 20% of coal capacity does not affect operational flexibility.
- NREL (2013), a case study based on a coal power plant in North America, discusses the evolution of a coal generation asset from baseload to peaking Plant, and establishes that a coal generating station can become a flexible resource. This flexibility — namely the ability to cycle on and off and run at lower output (below 40% of capacity) — requires limited hardware modifications but extensive modifications to operational practice.

These theories have also been proven in practice: Germany and the USA, countries where renewable energy penetration has increased significantly, have converted baseload coal plants into flexible ones to meet the requirements of renewable energy integration. In Germany, two units of the Moorburg plant (Agora, 2017), each with 800 MW capacity, have been converted to operate as flexible plants at minimum loads of 30-40%. In the Northern part of the USA (NREL, 2013), a coal-based power plant has been converted into a flexible plant that can operate at a minimum load of 40%.

3.2 Baseload coal plants require technical retrofits to operate flexibly

To meet flexibility requirements of increased renewable energy penetration, baseload coal plants would need to operate at much lower PLFs of 40-55% and with even higher ramp up and ramp down rates. This is not technically feasible for current coal plants, and therefore these plants would require retrofits.

In this section, we focus solely on retrofits targeted to convert baseload plants into flexible plants. We start by discussing why this is required, then dig deeper into the key components of flexibility retrofits in terms of its economic costs.

Currently, India's coal power plants are operating at an average PLF of 55-62% and are asked to cycle their load on a more frequent basis. This level of operations has technological implications as well as additional costs compared to higher PLFs and lower load cycle rates due to reduced efficiency of components, making operations even today economically unviable in many cases. Increased renewable energy penetration will increase flexibility requirements, which means that these coal plants would need to operate at even lower PLFs of 40-55% (NTPC, 2017) and with even higher ramp up and ramp down rates, operations not technically possible for current plant technologies and operations. Also, as most of these coal power plants are tied up in long-term PPAs, the incremental cost for converting these plants into flexible plants would require additional compensation beyond PPA tariffs to remain commercially viable.

To mitigate the impact of flexibility-based operations, plants will need appropriate retrofits allowing them to operate flexibly and at even at PLFs of 40% in a technically feasible manner.

A coal power plant can technically operate as a flexible power plant if it fulfills three key parameters: ability to operate with a reduced minimum load factor, reduced start-up time, and increased ramp up rate.

A coal power plant can operate as a flexible plant technically if it fulfills three key operational parameters: ability to operate with a reduced minimum load factor, reduced start-up time, and increased ramp up rate. To fulfill each of the aforementioned conditions, significant retrofitting would be needed. We have briefly summarized retrofitting options for each of the parameter in the Appendix (Table 6.2).

3.3 Investment requirements to convert a baseload coal plant into a flexible coal plant

As discussed in Section 3.1, flexible operations for coal power plants are technically feasible; however, converting baseload plants into flexible plants will incur additional costs. These additional costs require compensation so that the conversion into flexible power plants can be economically feasible for the project developer and investors. In this section, we discuss some benchmark[9] indicative costs[10] for converting a baseload coal plant into a flexible plant.

3.3.1 METHOD FOR CALCULATING INVESTMENT REQUIREMENTS

There are two approaches to compute the compensation required to achieve a commercially viable conversion of a baseload plant to a flexible plant: the cost-based approach and the market pricing approach. We have adopted the cost-based approach for computing the compensation required for converting a baseload coal plant into a flexible operation plant. The rationale of using this approach is discussed in Box 3.1.

In the cost-based approach, the incremental costs are divided into fixed and variable incremental costs and hence, if allowed, can be recovered through the existing hybrid tariff structure where the fixed cost component is paid in capacity or load terms (INR per MW) and the

9 We are mentioning the benchmark cost because these are derived from the CERC's benchmark cost parameters used in their tariff orders.

10 These are indicative costs because each plant will have different costs depending on the level of upgradation done for retrofitting, age of the project, existing technology etc.

variable cost is paid in energy terms (INR/kWh). Fixed incremental costs would include: (a) capital expenditure for the technical upgrades to the plant, (b) additional operating expenses for the flexible operation and maintenance; and, (c) loss of return on equity due to the reduced project life of the plant. Variable incremental costs would include incremental variable costs due to lower PLF. Box 3.2 provides the summary of the cost-based formula used to calculate the incremental costs required to convert a baseload plant into a flexible plant.

The incremental cost numbers are shown in net present value (NPV)[11] terms (INR Cr/MW) and levelized cost terms (INR/kWh) in Section 3.3.2. The former provides the amount of upfront investment that may be required to convert the baseload coal plant into a flexible plant

Box 3.1: Approaches used for compensating the conversion of a baseload coal plant into a flexible plant

There are two approaches to compute the compensation required to achieve a commercially viable conversion of a baseload plant to a flexible plant: (a) the cost-based approach and (b) the market pricing approach.

In the **cost-based approach**, we focus on the actual project level investment and expected returns to arrive at the required compensation for the flexible coal plant. This method of compensation -- a two-part tariff, with separate components for fixed and variable cost recovery -- ensures that the developer not only recovers the initial benchmark costs but also gets incentivized for its performance based on its operational efficiency.

In the **market pricing approach**, the project developer would be compensated in relation to demand and supply of flexible power requirements (ancillary market and services). In practice, using a market pricing approach for computing the compensation required for converting a baseload coal plant into a flexible operation plant requires an underlying market mechanism that can properly determine the price of the flexibility in relation to the demand supply scenario.

Since in India, only ~10% the energy is transacted using a market mechanism, this renders the market mechanism relatively very weak compared to long-term contracting arrangements, which are generally dependent on the cost-based approach. We have therefore adopted the cost-based approach for computing the compensation required for converting a baseload coal plant into a flexible plant.

Box 3.2: Incremental cost of converting a baseload coal plant into a flexible plant

The calculation for the cost-based approach is as follows:

(Incremental) Cost of Flexibility = Loss due to lower PLF leading to higher primary fuel cost (A) + Extra fixed cost required to convert a coal plant into a technical flexible plant(B) + Loss in ROE due to the reduced life of the plant due to flexible operation (C)

Where,

A = Primary Fuel Cost at PLF of a flexible plant (PLF 40%-60% range) - Primary Fuel Cost at PLF of 60% (new normal);

B = Interest rate for the new loan + Depreciation of the capex incurred + ROE expected after the retrofitting;

C = ROE component of the recovery cost lost due to reduced life of the plant

11 The NPV is calculated at the year when the plant is retrofitted to convert into a flexible plant, and not to time zero. This ensures that the comparison is made at the time the retrofit is made. The levelized cost is also calculated to the same year.

while the latter shows the effective additional levelized tariff that must be recovered to operate as a flexible plant in a commercially feasible manner.

The costs of the baseload coal plant are the baseline costs. We present each of the incremental costs as a factor of the baseline fixed and variable costs of a typical baseload coal project[12] to understand the cost-effectiveness of the conversion of a baseload plant into a flexible plant.

Table 3.1: Impact of technical upgrade costs on fixed costs of a plant converted into a flexible plant

CAPITAL COST FOR RETROFIT (INR CR/MW)	INCREMENTAL FIXED COST IN NPV TERMS (INR CR/MW, % OVER FIXED COST OF BASELOAD PLANT)	INCREMENTAL FIXED COST IN LEVELIZED TERMS (INR/KWH, % OVER FIXED COST OF BASELOAD PLANT)
0.70	7.96%	11.99%
2.30	24.01%	42.92%

Source: CPI Analysis

Please note that, though a typical coal power plant in India is compensated via a hybrid tariff structure where the fixed cost component is paid in capacity or load terms (INR per MW) and the variable cost is paid in energy terms (INR/kWh), we have presented the incremental costs of flexible operation in terms of capacity as well as energy for indicative purposes.

Since we are using a cost-based approach to present the incremental cost, we present these numbers under several scenarios of input cost parameters. In Section 3.3.2 we discuss each of the components in detail, leading to overall cost impacts.

3.3.2 INVESTMENT REQUIREMENTS

The capital expenditure for technical upgrades can increase fixed costs by 7.96% to 24% in NPV terms.

A typical thermal power plant goes through various retrofits during its project life for reasons such as improving plant efficiency, increasing flexibility, or extending the overall project life of the plant. Here, we focus on the retrofit capital cost required to increase the operational flexibility of a baseload coal plant. The more the need for flexibility, the higher the cost of retrofitting,[13] and hence the greater the overall investment requirement.

While the cost of retrofitting varies from plant to plant depending on the age of the power plant, technology used, type of primary fuel, etc., we have performed a scenario analysis using average capital cost numbers from German power plants. We consider a wide range of retrofit capital expenditure, from INR 7 million/MW to INR 20 million/MW. This incremental cost would be recovered as the fixed cost component of the tariff, which is comprised of depreciation, interest cost and return on equity. Table 3.1 shows that this incremental cost can be as high as ~24% of the fixed cost of the baseload coal plant in NPV terms and 43% in levelized terms.[14]

Modified operational expenses and maintenance to perform flexible operations can increase fixed costs by up to 0.80% in NPV terms.

According to NREL (2014), the increased number of cycles due to flexible operations can increase operating expenses by 5% of the total operating expenses i.e. by INR 0.01/kwh over baseline fixed cost. In NPV terms, this cost translates up to 0.80% of the baseline fixed cost.

Reduced plant life due to flexible operations can lead to loss of return on equity, which increases fixed costs by 2.3% in NPV terms.

Flexible operations for coal power plants lead to thermal and mechanical fatigue and stresses for various parts of the plant. These result in reduction of the expected life of the plant, which then leads to a reduction in the expected return on equity. This loss can be attributed as another incremental fixed cost for flexible coal.

We assume that a baseload plant with an expected life of 40 years can lose up to five years[15] of its useful life when converted to a flexible plant. The reduction in project life has a significant impact on the expected

12 We calculated the benchmark fixed and variable cost of a baseload coal plant using the CERC assumptions at normative parameters (please refer to Appendix 6.1). The baseline fixed cost of a typical baseload coal plant in our case is INR 5.45 Cr/MW (NPV at the year of retrofit) which translates to INR 0.93/kWh in levelized cost terms. Similarly, the baseline variable cost is INR 15.58 Cr/MW in NPV terms and INR 1.97/kWh in levelized cost terms.

13 The major components or subsystems, which will require the investment for upgradation or retrofitting to improve the flexibility, are boiler systems, control and communication systems, oil and fuel supply systems, coal mills, coal bunker and allocation systems, steam turbine etc.

14 The incremental percentage in the levelized cost is almost twice to that in the NPV cost due to the base effect i.e. baseline cost of project in levelized terms are relatively lower than that in NPV terms.

15 It is quite difficult to accurately determine the impact of flexibility operation on the expected project life of a coal plant. However, based on our primary research, we have assumed that the coal plant can lose up to 5 years out of its expected life of 40 years.

return on investment by the developer (or investors) as the majority of returns are expected to be recovered in the later years of a project. As shown in Table 3.2, the loss in return on equity (ROE) can add up to 2.3% over baseline fixed costs of the plant in NPV terms and 4% in levelized terms.

Lower plant load factors can increase variable costs by 3-9% of levelized variable costs.

When a baseload coal power plant operates flexibly, usually the plant is expected to operate in the 40-60% PLF range. The under-utilization of the plant's full capacity affects the fixed cost and the variable cost of the thermal power plant due to higher specific generation costs (INR/kWh) of the primary fuel.

The lower PLF means higher specific heat rate. This means that a greater amount of energy is required to generate each unit of power, or, in other words, more coal would be consumed to generate each unit of electricity. This inefficiency in fuel consumption leads to an increased per unit (of electricity) cost of consumption of primary fuel, a cost which can then be attributed to the flexible operation of the plant.

Since regulations do not allow for passing the higher cost of fuel to the consumer, these costs also impact the return on equity of the project developer. Thus, if the plant is operating at a lower PLF, it is important to recover this loss by passing it through in the variable tariff. Table 3.3 shows the impact of a lower PLF on the incremental cost of flexible plant.

The total incremental cost of converting a baseload coal plant into a flexible plant can be low -- in the range of 5%-10% of the total project cost of the baseload coal plant.

Combining all the component costs, the total additional cost of conversion can be in the range of 5%-10% of the baseload project's total cost in NPV terms and 8%-22% of the baseload project's total cost in levelized terms. These, though significant, are not excessively high; in fact, compared to other flexible options, flexible coal turns out to be a cost-effective option in the short-to-medium term (we discuss comparisons in Section 3.3.3).

Table 3.2: Impact of reduced project life of coal plant on fixed cost of plant converted into flexible plant

REDUCED PROJECT LIFE DUE TO FLEXIBLE OPERATIONS	INCREMENTAL FIXED COST IN NPV TERMS (INR CR/MW, % OVER FIXED COST OF BASELOAD PLANT)	INCREMENTAL FIXED COST IN LEVELIZED TERMS (INR/KWH, % OVER FIXED COST OF BASELOAD PLANT)
35 Years	2.29%	4.09%

Source: CPI Analysis

Table 3.3: Impact of reduced PLF of coal plant on variable costs of a plant converted into flexible plant

PLF	CAPEX FOR FLEXIBILITY (INR CR/MW)	INCREMENTAL VARIABLE COST IN NPV TERMS (INR CR/MW, % OVER TOTAL BASELINE PROJECT COST)	INCREMENTAL VARIABLE COST IN LEVELIZED TERMS (INR/KWH, % OVER TOTAL BASELINE PROJECT COST)
50%	2,585	2.28%	3.83%
40%	2,703	4.10%	8.63%

Source: CPI Analysis

Figures 3.1 and 3.2 show the upper bounds of these costs respectively. The remaining scenarios are shown in Appendix 6.4.

3.3.3 COMPARISON WITH OTHER OPTIONS FOR SUPPLYING FLEXIBLE RESERVES

The upfront investment costs of lithium ion batteries and pumped hydropower, the cleaner flexibility options, are 500%-2000% and 400%-1800% times costlier than the incremental costs of converting a baseload coal plant into a flexible plant, respectively.

In this section, we perform a high-level comparison of the total cost of converting a baseload coal plant into a flexible plant against the upfront investment cost of other technologies that can be used as flexibility reserves.

The two most promising technologies that can provide the desired flexibility for renewable energy integration are pumped hydro and lithium-ion storage batteries. According to NITI Aayog's work evaluating energy scenarios for India through 2047, the average capital cost of a lithium ion battery is approximately INR 14 Cr/MW and that of pumped hydro is INR 11.4 Cr/MW (NITI Aayog, 2016).

Hence, the upfront investment costs of lithium ion batteries and pumped hydropower, the cleaner flexibility options, are 500-2000% times and 400-1800% costlier than the incremental costs of converting a baseload coal plant into a flexible plant, respectively.[16] In addition, if we were to add the stranded cost of coal plants to the cost of batteries and pumped hydro, then this difference increases further.[17]

This noted, it is important that the cost of these cleaner options to provide flexibility come down as soon as possible so that India can transition to a low-carbon electricity system in an accelerated manner. In the meantime, coal seems to be a cheaper and more practical short-term solution for flexibility for a country like India even after levying the carbon price.

3.4 Other impacts of using coal plants as flexible reserves

In addition to costs and operations, converting baseload coal plants to flexible plants has several other implications on CO_2 emissions and renewable energy curtailment.

3.4.1 EFFECT ON CO_2 EMISSIONS

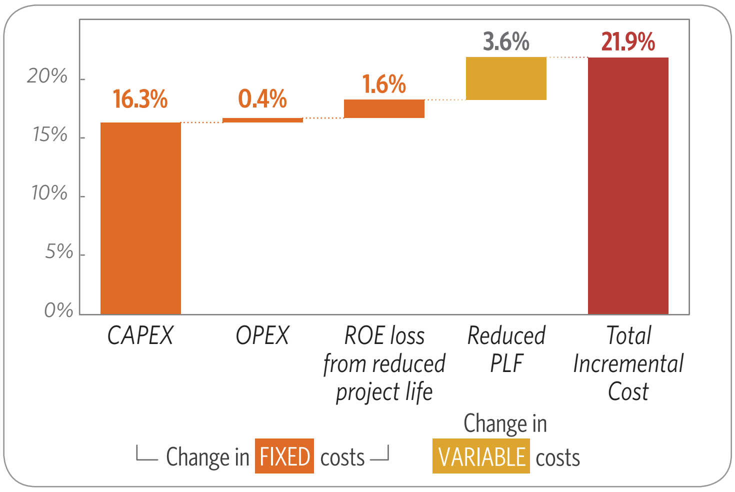
The utilization of coal plants as flexible plants will save CO_2 emissions of approximately 0.11 million tons/MW of power in absolute terms.

Assessing CO_2 emissions efficiency (gCO_2 emitted per kWh of electricity produced) from using coal to provide flexibility is difficult given that much depends on the type of retrofitting used in the plant and the overall operational load of the plant. In some cases, CO_2 emissions efficiency increases, while in other cases, it deteriorates.

However, in absolute terms, CO_2 emissions would reduce in the flexible operation mode (Table 3.4). This reduction is due to the reduction in the average load factor from normative levels of 85% to desired levels of 40%, and also due to the reduction in the total life of the coal plant from 40 years to 35 years.

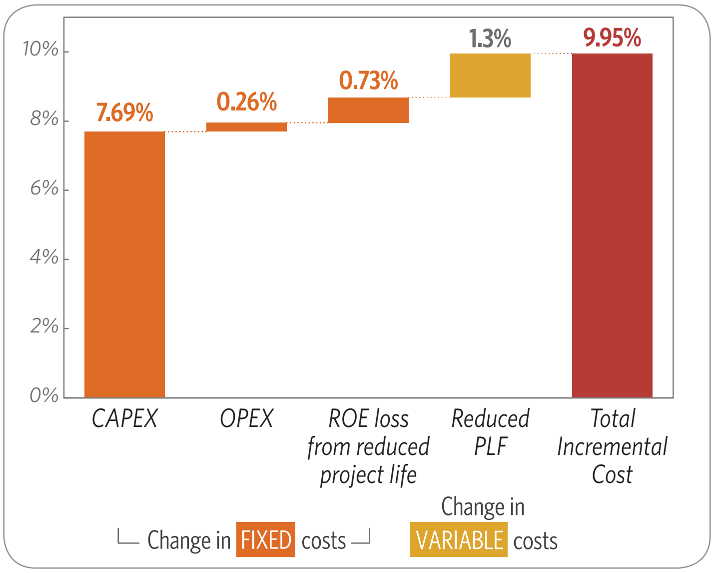
This stated, it is also important to note that further emissions reductions would be achieved through alternative flexibility options such as lithium ion batteries and pumped hydropower, thus, while flexible coal is the most cost-effective option, it is important to see it as a short-term solution while working to bring down the costs of cleaner flexibility options.

Figure 3.1: Indicative upper bound incremental cost in NPV terms of converting a baseload coal plant into a flexible plant



Source: CPI Analysis

Figure 3.2: Indicative upper bound incremental cost in levelized terms of converting a baseload coal plant into a flexible plant



Source: CPI Analysis

16 The numbers are calculated as the incremental capital cost of the lithium ion and pumped hydro over the total incremental cost (NPV) required to convert a baseload coal plant into a flexible plant.

17 If coal plants are not converted into flexible options, then there will be higher chance of these plants getting stranded. This means stranded cost should ideally be added to the flexibility cost of other technologies. In any case, this stranded cost will be an additional implicit cost to the overall system cost.

While flexible coal is the most cost-effective option currently, it is important to see it as a short-term solution while working to bring down the costs of cleaner flexibility options.

Table 3.4: Savings in CO_2 emissions due to flexible operation of coal plant

PLF	NET LIFE OF THE POWER PLANT	CO_2 SAVINGS (MILLION TONS/ MW)
40%	35	0.11
50%	35	0.09
55%	35	0.08

Source: CPI Analysis

3.4.2 EFFECT ON RENEWABLE ENERGY CURTAILMENT

As renewable energy penetration increases, a likely response is to simply curtail renewable generation when renewable tariffs are higher than fossil energy based tariffs. This is the case for much of installed renewable energy capacity. Lower PLFs of coal power plants operating as flexible plants would help to reduce renewable energy curtailment, making best use of power generated, especially if combined with better scheduling of renewable energy. According to NREL (NREL, 2017), lowering the minimum PLF of coal plants (to 40%) would reduce renewable energy curtailment from 3.5% down to 0.76%.

4. Market design requirements to enhance the flexible operation of thermal power plants

While our analysis uses cost-based compensation to estimate accurate costs for converting coal plants to flexible plants, one of the issues with cost-based compensation in practice is that it may not be as cost-effective for regulators as market-pricing compensation. Under cost-based compensation, regulators would need to calculate compensation on a plant-by-plant basis. This strategy could be gamed, resulting in not only higher compensation per plant but also selection of costlier options.

Instead, a cost-effective option for procuring flexibility would be the development of a power market including a market for flexibility. Given that most of the power (and related services) in India is procured using long-term contracting mechanisms, this solution requires further investigation.

Power market design needs to adopt measures to encourage use of flexible coal-based units when needed by the system; thus helping to integrate more renewables in the grid.

An important aspect that needs immediate attention is the design of the Indian power market to allow coal-based generating units to be used as a flexibility option in an economically feasible manner. Below we have discussed some of the measures that can be adopted to allow for more flexible coal-based power plants in the Indian grid:

- **Develop a market-oriented structure.** Power purchase agreements are currently designed on a cost plus basis. While this structure is good, it needs to be revised to recognize, compensate, and incentivize characteristics[18] needed to operate generating units in the power system when there is high renewable energy penetration. However, there are several barriers to development of such a market in India as discussed in the Appendix 6.3.
- **Modify regulatory practices.** Integrating renewables in a reliable and affordable manner requires considerable changes in the existing market design, regulatory framework, and grid practices. The conventional wisdom about the limitations of coal in renewable integration needs to be better understood. To this end, policymakers should formulate new rules and regulations, which should also increase the role of coal cycling in integrating renewables.
- **Define the need for flexibility services and allow all resources to offer their capabilities.** Market products should focus on meeting the specific flexibility need and letting all resources compete to provide the needed service. Focusing on the service desired should lead to products that take advantage of the differential qualities of resources, providing additional flexibility at the lowest cost.
- **Create value for flexibility.** The best way to create value for flexibility is to enhance pricing signals in energy markets including for coal-based flexibility. These include introducing scarcity pricing, which incentivizes resources to produce during times of need, and reserve shortage adders, which better reflect the value of resources to the system as it approaches a shortage.
- **Develop an auction market for flexible coal.** An auctioning mechanism for flexible coal plants should be envisaged so that they have the opportunity to weigh in their costs and returns. This will allow coal-based generators to bid for contracts which require them to have generating capacity available when flexibility is needed to integrate more renewable energy in the Indian grid.

18 These characteristics include minimum operating levels; ramping capacity; and short start-up, shutdown, and minimum up-/down-times; so that investments in power system assets can facilitate efficient system operations

5. Conclusion and future steps

India has embarked on a path to become a low carbon economy. Renewable energy may constitute as much as ~44% of the installed energy capacity mix by 2027, with the share of renewables in the electricity generation mix increasing to 23% by 2027.

In this study, we discuss two keys challenges faced by the Indian power system: higher flexibility requirements for higher renewable energy penetration and potential stranding of existing coal-based power plants. Both of these can be addressed in a cost-effective manner in the short-to-medium term by converting existing baseload coal plants to flexible plants. However, this transition will require compensation to existing plants in the order of 5-10% of total baseload cost in NPV terms.

Design of policy pathways and frameworks to facilitate this transition is the most important next step in this process. This would include regulations that support adequate compensation to coal power plants that are used as flexible resources. A further welcome step would be development of a capacity market to ensure cost-effective procurement of flexible capacity, including from coal and other sources.

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Appendix

Assumptions used to arrive at the incremental cost of converting a baseload coal plant into a flexible power plant

Table 6.1: Assumptions used in the model to calculate the incremental cost of flexible coal plant

PARAMETERS	BASELOAD COAL PLANT	FLEXIBLE PLANT	COMMENTS
Plant Availability Factor (PAF)	85%	85%	
Plant Load Factor (PLF)	60%	40%-55%	We assume that a flexible coal plant would operate in the range of 40%-60% PLF.
Total Plant Life (Yrs)	40	30	Due to increased frequency of ramping up and down of the plant, the life of the plant gets reduced.
Interest Rate	10%	10%	We assumed the same debt cost on the extra capex incurred to convert the base-load plant into a technically flexible plant.
Return on Equity (ROE)	15.50%	15.50%	We assumed the same ROE on the extra capex incurred to convert the baseload plant into a technically flexible plant.
Initial Capex for Baseload Plant (INR Cr/MW)	4.5	Not Applicable	
Additional Capex to convert the plant into a flexible plant (INR Cr/MW)	Not Applicable	0.70-2.3	Source: German case study We have taken scenarios for the capex number as it can vary from plant to plant
Additional Opex for flexible operation	NA	2-5% of the existing Opex	Source: German case study
Flexibility Implementation Year	12th Year		This is the year when the baseload plant is retrofitted to work as a flexible plant. We have taken 2 scenarios for this: 12th Yr and 15th Yr.
Other Assumptions	a) Fixed cost of a baseload plant will be recovered in full under the flexibility mode as well. b) Only the ROE component of the fixed cost during the reduced years will not be recovered due to flexibility and hence will require the compensation. Although depreciation component of the fixed cost will get modified due to reduced life and will increase the cost, overall depreciation cost will remain changed. In fact, the increased depreciation in the earlier years just after the flexibility is introduced will help to defer some of the tax to later years. c) Due to the reduction in PLF, the per unit quantity of the primary fuel will increase. This increment in the fuel cost is not allowed to recover as per the current regulations. Hence, this cost impacts the ROE of the plant. The compensation of this incremental cost should be part of variable tariff. d) Now when the plant is designed to operate as a flexible coal plant, the PLF will remain lower than 60%.The compensation required to recover cost will be equivalent to the increased cost of primary fuel when the PLF goes below 60%. We have considered 60% as the baseline PLF for the calculation of this component because the new normal of PLF in the industry is 60%. e) The additional Capex required for retrofitting to convert the plant from baseload plant to a flexible plant will be recovered as the additional fixed cost in the form of interest cost+depreciation+ROE		

Technology used for Retrofits for Converting a Baseload Coal Plant into a Flexible Plant

A coal plant needs to conform to the following three key parameters to be considered as an operationally feasible flexible power plant:

1. **Reduced minimum load or PLF:** The minimum load is considered the most crucial flexibility parameter. Given the fact that renewable energy penetration will continue to increase, fossil fuel plants will be required to respond quickly to keep the grid stable and match the changing power demand. Reducing the minimum load also provides a wider range of possible net power outputs. It also helps in avoiding expensive and CO_2 intensive shutdowns and start-ups. As discussed previously, to operate the plant below a PLF of 55%, specific retrofits would be required to reduce the minimum technical load of the plant to say 30-40%.
2. **Reduced start-up time:** The key reason to have a reduced start up time is that it enables a more rapid response to power demand. The retrofits done to reduce the start-up time helps in avoiding procedures that are complex and expensive since they usually require auxiliary fuel, such as oil or gas, during the ignition period.
3. **Increased Ramp rate:** Retrofits to increase the ramp rate is important as it allows dynamic adjustments to net power especially in increasing RE penetration.

A baseload coal plant needs technological upgrades and changes in operational framework to convert into a flexible plant. Table 6.2 shows some of the retrofitting options required for this conversion. All these options are from the pilot test done in some coal-fired plants in Germany. Depending on the kind of flexibility needed, a combination of some of these options can be deployed.

Table 6.2: Summary of retrofit options and their effect on parameters of flexibility

OPTIONS	REDUCTION IN MINIMUM LOAD	SHORTENED START-UP TIME	INCREASE IN RAMP RATE
Indirect Firing (IF): It is used to decouple the direct supply between mills and burners. It requires the use of a pulverized coal (PC) storage facility between coal mills and burners.	☑		☑
Switching from two mill to single mill operation	☑		
Control system and plant engineering upgrade improves the precision, reliability, and speed of control of temperature, pressure inside the boiler and feed-water mass flow in the water steam circuit, the load point of the coal mills and the turbine valve positions. It also includes the upgrades such as boiler or turbine.	☑		☑
Auxiliary firing with dried lignite ignition burner not only reduces the minimum load but also reduces the need for expensive fuels such as oil or heavy gas.	☑		☑
Thermal energy storage for feed water pre-heating can be used to store heat and release it at a later point. It helps in responding to power demand without changing the fire rate in the boiler.	☑		
Repowering involves placing a gas turbine upstream of the water-steam circuit in coal-fired plants as gas turbines can quickly ramp up compared to coal fired plant.		☑	☑
Optimized control system such as ABB's BoilerMax can be used for the online optimization of start-ups.		☑	
"New" turbine start allows cold steam to enter the steam turbine as quickly as possible after shutdown that enables the turbine to start with the boiler while it is still ramping up.		☑	
Reducing wall thickness of key components increases the allowable temperature change rate which eventually leads to faster start-up by boosting the ramp rate.		☑	☑

Barriers to development of a fully operational electricity market in India

There are several barriers to the development of a fully operational electricity market in India. Table 6.3 shows these and their impact on flexible coal generation.

Table 6.3: Barriers to development of electricity market in India

ISSUE	DISCUSSION	HOW IT IMPACTS COAL GENERATION	WAYS TO RESOLVE AND ALLOW MORE FLEXIBLE COAL CAPACITY
Almost 90% of the installed generation capacity tied up through long term agreements	Since the advent of the Electricity Act in 2003, there has been a continuous discussion of having a vibrant power market in India. However, there has been little progress in moving closer to a market based power system.	Most of the coal based power plants were designed to be base-load serving plants and hence are tied up for tenures as long as 30 years. While they recover the fixed cost, these power plants actually suffer on account of lower operational PLFs.	Develop a market-based structure where PPAs are developed with market design as a backdrop. Revise PPA structures (and market designs) to recognize, compensate, and incentivize the characteristics that would be needed to operate the power system under a high level of RE.
Under-developed SPOT market	The DAM[1] came into existence almost a decade back in India. Still the volumes that are traded on the SPOT market are miniscule as compared to the overall electricity transactions because of non-availability of large numbers of players (supply and demand), non availability of products suiting needs of different set of market players and non-availability of long term exchange traded contracts	Coal based generators generally have very limited capacity to participate into spot market and since the spot market is shallow with no long term products available, the coal based generators do not get a long term pricing view and refrain from participating into spot markets	An efficient mechanism through which the grid operators both at the state and regional levels have access to capacity reserves should be evolved. This may be achieved by withholding a part of the capacity in certain coal plants having higher ramping capabilities from daily scheduling and dedicating it for reserve margins
Non-uniform scheduling and dispatch code	IEGC has been discussing having a uniform scheduling and dispatch code for all power generation technologies and for all beneficiaries in India. However the renewable energy forecasting and scheduling is still to be developed and integrated fully with the national system operations	Not having scheduling and dispatch code for renewables puts additional pressure on coal based plants to provide for flexibility without having any incentive to do so.	Clarity on renewable energy grid code will help the central and state owned coal based generating stations to plan their operations better and contribute to meeting the reserve requirements needed in case of high renewable energy integration
No ancillary market	Ancillary market include all the necessary functions performed by the agencies involved in the generation, system operation, transmission, and distribution of electric energy to support the reliable delivery of power with stable frequency and voltage. While the concept of ancillary market has been afloat in India there has not been much progress on its actual implementation	Plant flexibility can take many forms, including the ability to start up and shut down over short periods of time, be run at a low minimum load, rapidly change generation output, and offer ancillary services to support system reliability.	Having an ancillary services market will allow the coal based power plant to participate in the market and provide real time balancing power. Some of the products/services include minimum operating levels, ramping, and short start-up, shutdown, and minimum up-/down-times to facilitate efficient system operations.

Incremental cost of converting a baseload coal plant into a flexible plant

As discussed earlier in Section 3.3, the cost-based approach used to arrive at the incremental cost of conversion of a baseload coal plant into a flexible one is indicative only as these costs vary significantly from plant to plant. Hence, we provide these incremental costs under several scenarios of PLF levels and capital expenditure required for retrofitting. This allows us to present these numbers covering a wide range of possibilities and input parameters.

Table 6.4: Incremental cost of converting a baseload coal plant into a flexible plant-scenario analysis

PLF	CAPEX FOR FLEXIBILITY (INR CR/MW)	INCREMENTAL COST IN NPV TERMS (INR CR/MW, % OVER TOTAL BASELINE PROJECT COST)	INCREMENTAL COST IN LEVELIZED TERMS (INR/KWH, % OVER TOTAL BASELINE PROJECT COST)
40%	0.70	5.76%	12.74%
50%	0.70	4.46%	7.88%
55%	0.70	2.83%	4.54%
40%	2.30	9.95%	22.01%
50%	2.30	8.65%	15.30%
55%	2.30	7.02%	11.28%

Source: CPI Analysis