Sustained cost declines in solar PV and battery storage needed to eliminate coal generation in India

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Abstract

Unabated coal power in India must be phased out by mid-century to achieve global climate targets under the Paris Agreement. Here we estimate the costs of hybrid power plants—lithium-ion battery storage with wind and solar PV—to replace coal generation. We design least cost mixes of these technologies to supply stylized baseload and load-following generation profiles in three Indian states—Karnataka, Gujarat, and Tamil Nadu. Our analysis shows that availability of low cost capital, solar PV capital costs of at least $250 kW$\textsuperscript{−1}$, and battery storage capacity costs at least 50% cheaper than current levels will be required to phase out existing coal power plants. Phaseout by 2040 requires a 6% annual decline in the levelized cost of hybrid systems over the next two decades. We find that replacing coal generation with hybrid systems 99% of the hours over multiple decades is roughly 40% cheaper than 100% replacement, indicating a key role for other low cost grid flexibility mechanisms to help hasten coal phaseout. Solar PV is more suited to pairing with short duration storage than wind power. Overall, our results describe the challenging technological and policy advances needed to achieve the temperature goals of the Paris Agreement.

More ambitious emission reduction targets for greenhouse gases than those submitted by countries' Nationally Determined Contributions are needed to achieve the temperature goals of the Paris Agreement [1–4]. This will require accelerated deployment of clean energy solutions such as wind power, solar power, and energy storage technology [4, 5].

India is the world's third largest emitter of carbon dioxide with roughly 40% of annual CO$_2$ emissions derived from coal power generation [6, 7]. India is rapidly deploying renewable energy and has pledged to achieve 50% of installed electricity capacity from non-fossil fuel-based energy resources by 2030 [8]. India also recently committed to achieving net-zero emissions economy wide by 2070 [8], although it is currently unclear if the net-zero target refers to only CO$_2$ emissions or all greenhouse gas emissions.

Previous modelling studies on the future of India's electricity sector have considered various scenarios with high levels of renewable energy penetration [9–11]. Such studies are usually based on capacity expansion and dispatch models that meet energy demand with investments in different energy sources. The complexity of these models inevitably requires several assumptions such as a well-functioning national electricity market and limited transmission, political, or institutional constraints. The relevance of such approaches is however limited in developing country contexts such as India, where electricity is not sold through fully deregulated markets, and where political and institutional constraints can be barriers to technology adoption [12].

Instead, our study focuses solely on a pivotal climate policy issue relevant for India's emissions trajectory and global emissions pathways—the possibilities of reducing coal power use in India through development of alternate energy sources that can provide the same generation profile to the electricity...
grid. We make minimal assumptions around the rest of the electricity system in India apart from the assumption of continued requirement of baseload and/or flexible power generation sources. We build an optimization model to study the least cost combinations of energy storage with wind and solar power—hybrid power plants—that can provide such power generation profiles. Our study, the first of its kind for India, builds on previous work studying the value and operation of energy storage systems for decarbonizing the U.S. electricity system \[13, 14\]. We estimate that the levelized costs of hybrid systems that provide flexible or baseload generation every hour over a twenty year period are currently in the range of \( \text{₹} 10–14 \text{ kWh}^{-1} \), assuming a lower cost of capital. To be competitive with currently operating or new coal power plants, costs must fall by at least 60%. An annual cost decline of 6% in both solar PV and battery storage could enable phase out of coal power beginning 2040 in India, broadly consistent with the power sector decarbonization goals necessary to limit global average temperature rise to 1.5 \( ^\circ \text{C} \) \[15, 16\]. This pace of cost decline can also avoid the construction of new coal power plants in the 2030s.

1. Methods

We focus on three states in India: Karnataka, Gujarat, and Tamil Nadu. These three states have relatively higher coal generation costs compared to other states as they are located further from coal mines which increases coal procurement costs \[17, 18\]. They are also considered part of the better performing group of Indian states in terms of renewable energy deployment \[19, 20\] with installed renewable energy capacity that is in the top five of all Indian states \[21\]. We draw on twenty years of hourly wind and solar output for site locations in these three states. Table 1 shows the average capacity factor (CF) for wind energy and solar energy at the selected site locations in the three Indian states we consider.

### 1.1. Renewable energy data

We undertook a multi-step process for gathering the required multi-year hourly wind and solar generation data for our site locations. First, proprietary wind and solar power production data normalized to plant capacity were obtained from project operators under Non Disclosure Agreement for six power plant sites (one each for wind and solar PV in each state) in the three states of Karnataka, Tamil Nadu, and Gujarat. In each state, the location of the wind and solar PV site was less than 100 km from each other to ensure that it could represent a potential co-located hybrid system. We used this data to create a typical year of generation of wind and solar power which provide us with the CFs shown in table 1. For more details on the process used to simulate a typical year of generation from our proprietary data, see Supplementary Information (SI) Note 1.

Second, we obtained 20 years of hourly wind and solar output based on Modern-Era Retrospective analysis for Research and Applications (MERRA-2) satellite reanalysis data for the period 2000–2019 (both years inclusive) for the same exact proprietary data site locations (see first step above) in Karnataka, Gujarat and Tamil Nadu. MERRA-2 has a horizontal resolution of 0.5\(^\circ\) by latitude (\(-90^\circ – 90^\circ\)) and 0.625\(^\circ\) by longitude (\(-180^\circ – 179.375^\circ\)) with 361\times 576 grid cells worldwide \[22\]. Solar irradiance data is converted into power output based on the Global Solar Energy Estimator model \[23\]. Wind speeds are converted into wind turbine power output using the Virtual Wind Farm model \[24\]. We use the same wind turbine (hub height and power curves) and solar panel (azimuth angle, tilt angle, and tracking selection) configurations as used by the developers at the sites in these states to maintain consistency with our proprietary data. For more details on this, see SI note 1.

In the third step, to account for the fact that wind and solar output from reanalysis data such as MERRA-2 can have issues with CFs not matching real world observed CFs, we scale the median of the 20 years of reanalysis data CFs to the observed CFs from the proprietary data (table 1) we have for these states (we scale the MERRA-2 data by the ratio between our proprietary data CF and the median CF of the 20 individual years of MERRA-2 data).

This approach, where we draw on the reanalysis data for incorporating the temporal and spatial characteristics of the resource over multiple years, but scale the data to real world observed data for CFs (which in our case were obtained at the plant level from industry developers) has been recently outlined in Tong et al \[25\]. The unscaled CFs for the raw MERRA-2 based dataset at the proprietary site locations our shown in tables S11, S12 and S13 in SI note 4.

In the absence of any publicly available multi-year wind resource data for India, previous studies \[9–11\] are based on a single year of national wind resource data published by the National Renewable Energy Laboratory \[26\]. To our knowledge, this is the first study on India to use multiple years of both wind and solar power production data. Our modeled

| State       | Technology | Average CF |
|-------------|------------|------------|
| Karnataka   | Wind       | 22%        |
|             | Solar      | 19%        |
| Tamil Nadu  | Wind       | 19%        |
|             | Solar      | 20%        |
| Gujarat     | Wind       | 23%        |
|             | Solar      | 20%        |

Table 1. Average CF for wind and solar at our selected site locations in Karnataka, Tamil Nadu, and Gujarat.
hybrid plants have an expected lifetime of 20 years so we run our optimization model over the full 20 year period using the entire scaled MERRA-2 based wind and solar dataset.

1.2. Robustness checks
We performed multiple checks using different available data sources for wind and solar generation to ensure robustness of our results. For more on this see supplementary note 4. Overall, we find that our results, i.e. suitability of solar for pairing with lithium-ion battery storage and the high cost of hybrid systems today compared to existing coal plants in India, are both robust to alternate data inputs.

We also find, consistent with existing literature on the subject [27, 28], that just a small portion of hours in the twenty year dataset are significantly influencing the design of the system and as a result, driving up costs. These results affirm once again the need for multi-year resource datasets for electricity planning. A detailed exploration of wind and solar resources in the three states is provided in SI note 5. We find high seasonality for wind generation with significant generation during the monsoon period (June–September) and limited output for the remaining parts of the year. Wind also has notable inter-annual variability in output. Solar output is found to be more consistent both across years and seasons.

1.3. Coal plant generation profile
We consider two types of stylized generation profiles for coal power as useful bounding cases for estimating the cost of replacing coal power generation with hybrid power plants. First, the target coal plant to be replaced is assumed to run as inflexible baseload, providing 100 MW of power every hour of the year, as shown in figure 1(a). While inflexible baseload operation may be a useful limiting case to understand the costs of such systems, coal plants in India are increasingly run in a flexible manner to incorporate higher shares of wind and solar generation in India. At times of high wind and solar production, coal generators often back down to lower levels of output, rising again to maximum output during the evening hours as demand rises and solar generation drops off. If the objective is to replace a dispatchable source of power such as flexible coal plants rather than firm inflexible baseload, grid operators may require hybrid power producers to similarly reduce output during hours where standalone wind or solar plants without battery storage are producing at full capacity. We therefore model a second stylized operational profile for coal power shown in figure 1(b). For the stylized flexible generation profiles, we incorporated data on the relative shares of already installed stand-alone (without energy storage) wind and solar PV capacity in each state. A detailed description of how we developed the stylized profiles for flexible generation is provided in note 1 of the SI. Note that while figure 1 only shows an average 24 h period, our optimization model uses the full time varying twenty year hourly target profile, which differs from the 24 h average profile in the case of flexible generation.

1.4. Model
We build on the framework described in Ziegler et al [13]. In this optimization problem, the design objectives are the capacity of the solar plant, wind plant and battery that must be built; the charging and discharging decision for the battery system at each time step; and the rate of charge or discharge. The objective is to minimize the levelized cost of energy (LCOE) of the hybrid system, which is simply the present value of all costs divided by the total energy sold by the system over its lifetime.

The optimization objective is based on the full 20 years of operation (175 200 h). The costs are composed of capital costs including installation costs of the battery system, wind plant, and solar PV plant. We ignore operating costs such as maintenance given that capital costs far outweigh operating costs for renewable energy [13, 27].
This optimization problem is constrained foremost by the target output profile of the coal plant that the hybrid system must match. Further, the operation of the battery is constrained to the maximum rate of charge or discharge, the energy level from one time step to the next, and the maximum and minimum energy level. These further bound the problem.

Our optimization problem is a Linear Programming problem which is therefore convex and quickly yields globally optimal solutions. Solar, wind and battery storage system capital costs are assumed as $700 kW$\(^{-1}\), $1100$ kW$^{-1}$, and $400$ kWh$^{-1}$ respectively [29–31]. Storage duration is assumed to be 4 h with a roundtrip efficiency of 75%. Plant lifetime is assumed to be 20 years. All model equations and associated parameters are summarized in SI note 1 (table S1).

2. Results

The LCOE of a hybrid system with an optimal mix of wind and solar capacity with short duration lithium-ion storage to provide the respective profiles of generation are shown in figures 2(a) and (b). We estimate the LCOE for different assumptions about the weighted average cost of capital (WACC). The individual capacities of wind, solar PV, and battery storage that make up the optimal hybrid power plant for each state and type of generation profile are shown in table 2. The results presented in figure 2 and table 2 show that solar is dominant in the hybrid power plant for each state and type of generation considered. Solar is found to be more suitable for pairing with lithium-ion battery storage in the states considered given its more predictable output across seasons as well as its lower cost compared to wind.

For a sensitivity analysis on the impact on LCOE from changes in storage lifetime, duration, and efficiency see SI note 2. More details on solar and wind generation and robustness checks on our renewable energy data are provided in Methods and SI supplementary notes 4–5.

The results shown in figure 2 indicate that hybrid systems are currently more expensive than the marginal cost (which includes fuel, operations, and maintenance cost) of the coal power plants operating in those states today, represented by the dashed black line at ₹3.0 kWh$^{-1}$ [32, 33]. Further, levelized costs of the system are roughly similar across both flexible and inflexible generation profiles. Baseload systems are cheaper as they sell more power to the grid across the operational lifetime and therefore lead to greater utilization of the capital investments. Assuming a lower cost of capital of 2.5%, baseload and flexible hybrid systems have levelized costs between ₹10–14 kWh$^{-1}$ which is several times the cost of existing coal generation in those states.

2.1. Mixing wind and solar power
To understand the relative value of each intermittent renewable technology, we model different mixes of wind and solar PV in a hybrid system with 4 h battery storage. Figure 3 shows the change in the levelized cost of the system providing baseload generation for different shares of wind and solar PV capacity in the total renewable energy capacity of the plant.

Costs of hybrid systems which only incorporate wind energy with storage are significantly higher at the sites considered. This is due to the high seasonality of wind generation in India (also see SI notes 4–5), with high output during monsoon season and very limited output the rest of the year. As such, wind is a poor companion to short duration storage for providing baseload or flexible generation every hour of the year. As solar is added to the hybrid mix, costs fall. Hybrid systems which combine even small amounts of wind capacity are cheaper than a system with only solar PV and storage for each of the three sites considered. For example, table 2 shows that this is the case for Karnataka and Tamil Nadu for replacing baseload generation, with just 1% and 7% of the wind-solar capacity coming from wind power. We do note that really small sized wind plant capacities (e.g. 14 MW) may not be practical as part of a hybrid plant, even if they are optimal. Figure 3 however shows that the LCOE of hybrid power plants with 0%–25% wind share are relatively similar, indicating that there may not be large trade-offs in optimality vs practicality in the design of hybrid power plants. The equivalent analysis for flexible generation is shown in SI supplementary note 2 (figure S1).

The behavior of the battery storage system both in terms of a 24 h average across the 20 year period as well as the hourly SOC across the full 20 years is shown in SI note 2 (figures S2–S5).

3. Reducing the cost of hybrid systems

In this section we explore two different levers for reducing the cost of hybrid systems. These include: drawing on wind and solar resources from a wider region to smooth variation in output and reducing the availability requirement of hybrid plants. In SI section 2 we also consider a third lever: monetizing excess generation that is normally curtailed.

3.1. Hybrid systems with reduced availability
Hybrid systems will also be allowed downtime, similar to coal power plants in India that often operate at 60%–80% CF for the year [34]. We define system availability here as the percentage of hours over the operational lifetime where the hybrid power plant is able to provide the required generation profile (baseload or flexible). While the results presented in figure 2 are for 100% availability systems, here we model the levelized costs of hybrid plants with lower than 100% availability, where the constraint of
Figure 2. Figure shows the LCOE for least cost hybrid systems in Karnataka, Tamil Nadu and Gujarat, for different assumptions around the weighted average cost of capital. LCOE values are shown in both ₹ kWh$^{-1}$ and $$/c kWh$. We assume a fixed conversion rate where $1 = ₹ 70$. (a) The LCOE of hybrid systems with an optimal mix of wind power, solar PV and battery storage for each state and WACC that can provide baseload generation shown in figure 1(a). The color of the bars indicates the share of solar in the solar-wind optimal mix. The dashed black line represents the marginal cost of coal power plants operating in those states today. (b) The LCOE of hybrid systems with an optimal mix of wind power, solar PV and battery storage for each state and WACC that can provide the flexible generation shown in figure 1(b). The color of the bars indicates the share of solar in the solar-wind optimal mix. The dashed black line represents the marginal cost of coal power plants operating in those states today.

Table 2. Capacity sizes of the hybrid power plants that mix the optimal combination of wind power, solar PV, and 4 h duration Li-ion battery storage to provide the target profile of generation at least cost.

| State       | Generation Type | Wind (MW) | Solar (MW) | Solar % in wind-solar mix | Battery Storage (MWh) |
|-------------|-----------------|-----------|------------|--------------------------|-----------------------|
| Karnataka   | Baseload        | 14        | 1685       | 99%                      | 2727                  |
|             | Flexible        | 0         | 1582       | 100%                     | 2553                  |
| Gujarat     | Baseload        | 371       | 1136       | 75%                      | 2038                  |
|             | Flexible        | 376       | 1058       | 74%                      | 1761                  |
| Tamil Nadu  | Baseload        | 109       | 1550       | 93%                      | 2606                  |
|             | Flexible        | 0         | 1154       | 100%                     | 2898                  |

Figure 3. Figure shows the LCOE for different shares of solar PV in hybrid systems providing baseload generation. LCOE values on the $Y$ axis are indexed to the LCOE for a hybrid system with only wind power and battery storage. (a) Results for Karnataka. The optimal mix shown with the red dot has 99% solar PV and 1% wind capacity. (b) Results for Gujarat. The optimal mix shown with the red dot has 75% solar PV and 25% wind capacity. (c) Results for Tamil Nadu. The optimal mix shown with the red dot has 93% solar PV and 7% wind capacity.

meeting the required generation profile is relaxed for some hours [13] in the 20 year period. A 100% system meets the generation required for all 175 200 h in 20 years. A 90% system would meet this requirement for 157 680 h. Results for these different scenarios are shown in figure 4 below for the case of baseload generation.

As the required availability of the system is reduced, levelized costs fall. Crucially, lowering the availability required by just 1% point from 100% to
99% leads to a roughly 40% reduction in levelized costs across the three states. Hybrid systems that can provide baseload generation 99% of the hours over 20 years are therefore notably cheaper than those that provide the generation 100% of the hours. This shows that a small share of hours in the 20 year period are driving the high cost of hybrid systems that meet the generation requirement 100% of the time. Tables S2–S4 in the SI note 2 show why this is the case. In the 99% system, the size of the battery storage system is much lower, reducing costs compared to the 100% system. A small share of hours with prolonged low output from wind and solar over the 20 year period requires bigger battery sizing for the 100% system, and therefore leads to much higher costs overall. By reducing the availability requirement even slightly, the hybrid system can rely more on wind and solar resources instead of the battery, reducing costs. Costs fall further as the availability required is further lowered as shown in figure 4. We also find that as the availability required is lowered, the share of wind in the wind-solar mix increases (figure 4, tables S2–S4).

For example in Karnataka, the hybrid system providing baseload generation in 100% of hours has just 1% of wind in the wind-solar mix. However, in 80% system is a wind dominated hybrid plant with 51% wind capacity in the wind-solar mix. Similarly for Gujarat, the share of wind goes from 25% in the 100% system to 62% in the 80% case, with steady increases in the wind share for each level of lower availability. In fact as the availability required is lowered, wind substitutes for storage in the hybrid system, which is what drives the cost reductions. We find that in Gujarat, an optimal mix hybrid system that provides baseload 100 MW power in 80% of the hours over 20 years has a lower levelized cost than ₹ 3.0 kWh⁻¹ (figure 4), the target for replacing existing coal generation. We caution however that these results do not necessarily mean that hybrid plants at 80% CF are cheaper than 80% CF coal power plants. The issue is that the precise timing of their availability will influence system and therefore consumer costs for grid electricity. The results shown in figure 4 are based on modelling downtime when it optimal for the hybrid plant operator, which due to the relative costs of wind, solar and storage, is when renewable generation is lowest and the battery would be needed most to fulfil the constraint of providing the target 100 MW generation. Of course, it is precisely when renewable generation on the electricity grid drops to low levels that coal generation today would likely be running at high output. Therefore, it is unlikely that hybrid plants will be allowed to have downtime in those hours if they are replacing coal power on the grid, as intended here. If so, other resources such as diesel generation or demand response may be required which incur their own costs. As such, we caution that while levelized costs for such systems fall in all the three states as availability is lowered to more realistic operational availability of less than 100%, this does not necessarily imply that coal generation can be replaced at those lower costs. Nevertheless, the results shown here can shed some light on the influence of system availability on levelized costs and also highlight the opportunities for other low cost grid flexibility mechanisms such as demand response or bi-directional electric vehicle charging which could potentially cover the 1% or 10% of hours over twenty years at a lower cost than the cost difference between 100% availability and 99% or 90% availability hybrid systems.

3.2. Geographical smoothing of wind and solar resources
Our results so far have focused on hybrid power plants at a single site, drawing on co-located (<100 km apart) wind and solar resources in a single location along with a battery storage system. However, wind resources in particular may have high spatial heterogeneity. Drawing from resources in multiple locations could lead to reduced costs, as dips
in output in one location could be compensated by another, smoothing the output profile of the variable renewable resource with potentially lower dependence on the battery and an increased role for wind energy.

To model this, we draw on twenty years of hourly wind and solar data in four individual sites in the northern, southern, eastern, and western parts of each state. The exact locations for each of the states are shown in SI figure S6. We model the levelized costs of hybrid power plants at each of these individual site locations. Then, we consider a fifth case, by averaging the hourly wind and solar output across these four individual locations to what could potentially represent a state averaged renewable resource, and model a hybrid system based on this state averaged resource. Comparisons between the costs of hybrid systems which can draw output from multiple locations versus the costs of hybrid systems that are located only in individual locations can help shed some light on how geographical smoothing of resources influence the design and costs of hybrid power plants for providing baseload or flexible generation.

Table 3 shows the results for the state of Gujarat. Similar results for Karnataka and Tamil Nadu are shown in tables S5 and S6 in the SI.

We find that smoothing resources over a wider region in Gujarat leads to lower levelized costs, and savings of 16% over the lowest cost individual location (West) and savings of 28% over the most expensive individual location considered (East). We caution however that the levelized costs for hybrid power plants based on the state averaged resource do not necessarily fully represent the costs of replacing coal generation. This is because to this cost one must also add the cost of transmission, functioning real time electricity markets, and other soft and hard infrastructure required to integrate renewable resources from different corners of a state. We also note that even with state averaged resources, wind continues to have a minor role, with the least cost hybrid system solar dominated in each of the three states (table 3, SI tables S5 and S6). Finally, the costs of such hybrid plants based on state averaged resources nevertheless continue to far exceed the ₹ 3.0 kWh\(^{-1}\) cost target required to compete with existing coal generation.

4. Implications for coal plants and global climate targets

Most global emission pathways compatible with limiting global average temperature rise to 2\(^\circ\)C call for complete phaseout of unabated coal power plants by 2050 [15, 35] while in order to limit temperature rise to 1.5\(^\circ\)C, unabated coal power generation should end by 2040 [15, 16].

We assemble a database of currently operational coal power plants in the three states (see SI section 1). India’s coal fleet is relatively young [15, 36] as are the coal plants in our selected states of Karnataka, Tamil Nadu and Gujarat. We find a capacity weighted averaged age of just 13 years for the fleet across these states. Assuming a 40 year lifetime for operational plants [36, 37], figure 5 shows the retirement timeline for currently operating coal power plants in Karnataka, Tamil Nadu and Gujarat.

Figure 5 shows that a phaseout of existing plants by 2040 or 2050 would either require policy intervention or displacement by lower cost alternate sources of generation, given the relatively small share of capacity likely to naturally retire by those dates. Any such phaseout would therefore strand a substantial share of existing coal capacity. This stands in contrast to other countries such as the United States for example, where a majority of coal power capacity is scheduled to naturally retire by 2035 [38]. A 2040 phaseout target in India strands more than 75% of coal capacity across the three states while a 2050 target leads to earlier than planned retirement for up to 60% of the fleet. Note that while our analysis shown in figure 5 focuses on plants in three states, high shares of stranded capacity from a 2040 or 2050 coal phaseout in India holds true across the country [15]. This suggests that implementing policies that can achieve such phaseout targets might be politically and economically unpalatable, particularly given the strong governmental support coal has historically enjoyed in India [39]. Further, avoiding coal generation for the 20 year operational lifetime of the hybrid power plant will avoid several million tonnes of CO\(_2\) emissions. We calculate the $/t CO\(_2\) abated. Table S7 in the SI shows that the current mitigation costs for hybrid systems across different assumptions for the cost of capital exceed estimates of the social cost of carbon (SCC)

| Location | Solar CF | Wind CF | Solar (MW) | Wind (MW) | Battery (MWh) | Solar % in least cost mix | LCOE (Rs kWh\(^{-1}\)) |
|----------|----------|---------|------------|-----------|---------------|--------------------------|-------------------------|
| North    | 25%      | 27%     | 1907       | 69        | 2102          | 97%                      | 11.5                    |
| East     | 24%      | 27%     | 827        | 287       | 3489          | 74%                      | 11.7                    |
| South    | 23%      | 33%     | 1617       | 170       | 2351          | 90%                      | 11.5                    |
| West     | 24%      | 33%     | 1271       | 205       | 2114          | 86%                      | 10.0                    |
| State avg.| 24%      | 30%     | 1232       | 138       | 1581          | 90%                      | 8.4                     |

Table 3. Levelized costs and capacity mix of hybrid power systems providing 100 MW baseload power over 20 years in the state of Gujarat at different individual site locations and a state averaged location which averages out resources from the four individual locations. All levelized costs shown are based on a 2.5% cost of capital. Note that similar results for Karnataka and Tamil Nadu are shown in the SI tables S5 and S6.
commonly used in policymaking. However, we do note that the mitigation costs associated with base-load hybrid power plants across the three states, for up to a 5% cost of capital, are less than the most recent estimate of the SCC based on an updated scientific understanding of climate impacts [40]. Finally, we also undertake an analysis for the benefits of avoided premature mortality from coal generation and this is provided in SI Note 3. We find that the benefits are of the order of ₹ 1 kWh$^{-1}$. As per the results in figure 2, this is clearly insufficient to bridge the gap between the current costs of hybrid systems and operating coal power plants.

Naturally, phaseout may prove politically easier if alternate clean technologies such as hybrid systems can provide power at lower costs than existing coal generation, i.e. < ₹ 3.0 kWh$^{-1}$ [32, 33]. From the results shown in figure 2, that will require significant cost reductions from today’s costs across the three states, even with assuming a lower cost of capital of 2.5%.

4.1. Future cost reductions

Wind, solar PV, and lithium-ion battery storage have all seen rapid cost declines in recent years [29, 41] which provide evidence towards future lower costs for hybrid systems. For instance, global weighted installation costs of wind and solar PV have fallen 24% and 79% respectively between 2010–2019 [29]. Meanwhile, lithium-ion battery pack prices have fallen 89% between 2010–2020 [42].

We examine the future cost targets these technologies (wind, solar PV, battery storage) would have to hit, to enable levelized generation costs that can economically displace coal generation and achieve the goals of the Paris Agreement. To understand various scenarios of displacement, we consider different cost scenarios for coal generation. Recent governmental directives have called for the introduction of pollution control technologies that could increase marginal costs by up to 25% [33]. Current cost of coal generation in India also does not account for the health or climate externalities imposed by coal power, aside from a small ₹ 400/ton cess on coal production. We therefore consider cases where a carbon tax as low as $20/ton CO$_2$ to as high as $60/ton CO$_2$ is imposed, decreasing the relative competitiveness of coal versus alternate generation technologies. For the levelized cost of new coal generation we assume costs of roughly ₹ 4 kWh$^{-1}$ [17]. We consider baseload hybrid systems with 99% availability, i.e. hybrid systems that provide baseload 100 MW power for 99% of the hours over a twenty year period. We focus here on 99% and not 100% systems as it clearly conceivable that in the future other low cost grid flexibility mechanisms (e.g. bi-directional electric vehicle charging) could handle the lean 1% of hours, which as shown previously in figure 4 significantly increase the cost of hybrid power plants.

Figure 6 shows the levelized costs of hybrid systems for different capital costs of wind, solar PV and battery storage, in the three states of Karnataka, Gujarat, and Tamil Nadu. All costs are assuming a lower cost of capital of 2.5% and shown for providing a baseload generation profile (note that as shown in figure 2), costs for both flexible and baseload generation are not too dissimilar). Note that while figure 6 only shows the cost of battery storage capacity, total storage system costs including balance of system costs, power costs, and controls are normally twice that of storage capacity costs alone [30, 31]. So a $75 kWh$^{-1}$ capacity cost translates to a storage system cost of $150 kWh$^{-1}$ in our model. Levelized costs of hybrid systems today, previously shown in figure 2, are also shown here in the upper left quadrant in

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**Figure 5.** Retirement timeline for coal power plants across the three states of Karnataka, Gujarat and Tamil Nadu assuming a natural 40 year plant lifetime. The red line is measured on the Y axis on the left and plots the cumulative share of total capacity that is beyond its typical lifetime. The stacked bars are measured on the secondary Y axis on the right and plot the amount of coal capacity, based on ownership, that is scheduled to retire in each year. Total operational coal capacity across the three states is 39,000 MW.
Figure 6. Figure shows the levelized costs of hybrid systems that provide baseload 100 MW power for 99% of the hours across 20 years for different combinations of capital costs for wind power, solar PV, and lithium-ion battery storage technology, in each of the three states of (a) Karnataka, (b) Gujarat, and (c) Tamil Nadu. The policy range in which each cost estimate falls is depicted by different colours, explained by the legend on the right. All hybrid systems shown in the figure are solar dominated in the wind-solar mix.

each row (state) in figure 6 and correspond to installation costs of $700 kW$^{-1}$ and $1100 kW$^{-1}$ for solar PV and wind respectively and battery storage capacity costs of $200 kWh$^{-1} (or total storage system costs of $400 kWh$^{-1} $[29–31]$. At these levels, levelized costs for 99% availability systems are in the range of ₹6–8 kWh$^{-1}$ as discussed previously in figure 4. This would require a $60/ton carbon tax to displace potential new coal generation.

Figure 6 shows that to displace existing coal with 99% availability hybrid systems across all the three states, without any policy intervention, would require cost targets of at least $250 kW$^{-1}$ for solar PV along with battery storage capacity costs of $100 kWh$^{-1}$. This corresponds to a 50% cost reduction for energy storage and more than a 60% cost reduction for solar PV. If the objective is to displace coal power by 2040 in line with the goals of the Paris Agreement [15, 16], then this cost reduction must be achieved in the next two decades, consistent with an annual year on year cost decline of roughly 6%. An annual decline of 6% will also mean that by 2030, hybrid systems will be cheaper than new coal generation in all three states without any carbon taxes or economic incentives for clean energy.

Note that the results shown in figure 6 correspond to a 2.5% cost of capital. However, if we consider higher capital costs which are more common in financing of clean energy projects, even more ambitious cost declines in the next two decades would be necessary for hybrid systems that are cost competitive with coal generation in India.

Figure 6 also shows that the relative resources of solar and wind influence the nature of cost declines for each state. For example, in Gujarat which has the highest share of wind generation in an optimal mix hybrid system, cost reductions are achieved through a fall in costs of any of the three technologies, illustrated by the pattern shown in figure 6(b). However, for Karnataka and Tamil Nadu, cost declines are mostly influenced by the capital cost of solar PV and storage as in these states wind is a small share of the optimal hybrid system, even in cases where wind capital costs are lower than solar PV (figures 6(a) and (c)).

5. Discussion

High capital costs for battery storage and highly seasonal wind generation make it expensive to currently replace coal generation in India with hybrid power plants, even in states with relatively higher coal generation costs. However, falling costs for these technologies together with project financing at lower interest rates can help bridge the gap. Access to capital at low costs, for example through the Green Climate Fund or international development assistance, will be critical to expanding the penetration of clean energy in developing countries such as India [43–46]. Even then, battery storage capacity costs at least 50% cheaper than current costs and wind and solar PV capital costs that are at least 60% lower than today’s levels will be required to phase out existing coal generation in India without economic incentives for clean energy or carbon taxes. A year on year decline of 6% in the
The levelized cost of hybrid systems over the next decade can help avoid the construction of new coal power plants beginning 2030 and achieve phaseout of existing plants by 2040, consistent with the goals of the Paris Agreement. Policy solutions such as allowing for excess wind and solar generation from hybrid plants to be contracted separately as well as technological improvements in low cost grid flexibility mechanisms can help further lower costs and accelerate the timeline of coal phaseout.

We find that solar PV is more suited to be paired with short duration storage in a hybrid system across the states considered, although blending in some amount of wind capacity can reduce the levelized cost compared to a system with only solar PV and storage. India should adopt a differentiated strategy, focusing first on those states where the variable cost of coal is highest, and gradually use renewable energy with storage to displace coal in other parts of the country as the costs of hybrid systems fall.

6. Limitations

Finally, we note a few limitations of this work. First, the target coal generation profiles, for both the base-load and flexible cases presented in figures 1(a) and (b), are hypothetical. Actual annual generation at coal power plants will differ from this stylized profile. Coal power plants also do not run for all hours of the year and therefore hybrid systems will also be allowed to have downtime. In the absence of plant level data for coal generation we believe our methods to be a useful approximation and that the two profiles can provide a bounding estimate on costs. As an additional robustness check, for Karnataka we collected confidential data from the Karnataka Power Transmission Corporation Limited of the hourly net load for the state in 2018, which is defined as the hourly electricity demand in the state minus the hourly generation from intermittent renewable energy located in the state. The data were then normalized to a maximum of 100 MW and used as a target coal generation profile in the optimization model. Results are show and discussed in SI Supplementary Note 6. The optimized configuration and levelized costs for a hybrid system replacing this profile of generation do not differ significantly from a system replacing our stylized flexible coal profile for Karnataka, offering reassurance that our stylized profiles are not driving our results. We do also note that for some individual coal power plants, output is reduced to almost zero during the monsoon months when wind and hydro power generation is at maximum levels. Incorporating these dynamics would likely further skew the results in favor of combining solar PV with short duration storage as no coal generation would need to be replaced when wind is generating at full power.

Second, we only consider short duration storage in the form of lithium-ion batteries and do not consider long duration (>10 h) storage solutions. Long duration storage technologies such as flow batteries, thermal storage solutions, or hydrogen based storage are yet to mature and be deployed at scale anywhere in the world. Short-duration storage accounts for approximately 93% of total global storage power capacity [47]. We believe that focusing on mature technologies that are available today, have already been deployed in India, and have seen consistent cost declines, would be more valuable to researchers, policymakers, and industry actors. Nevertheless, we note that low cost long duration storage technologies could play a valuable role in decarbonizing electricity [27]. Availability of such technologies in India could hasten the pace of coal phaseout and merit further research.

Third, and finally, large scale deployment of wind and solar power to phase out coal generation may create land-use conflicts with local communities in India given the large footprint of variable renewable energy resources and India’s high population density [48, 49]. This may particularly be the case for hybrid power projects with co-located wind and solar plants. We do not model the additional costs that may be associated with the difficulties of land acquisition.

Data availability statement

Twenty year MERRA-2 based wind and solar input data for the proprietary site locations in the three states is publicly available at https://tinyurl.com/india-solar-storage.

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