Environmental Research Letters

ACCEPTED MANUSCRIPT • OPEN ACCESS

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To cite this article before publication: Aman Malik *et al* 2020 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ab8033

Reducing stranded assets through early action in the Indian power sector

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Abstract

Cost-effective achievement of the Paris Agreement's long-term goals requires the unanimous phase-out of coal power generation by mid-century. However, continued investments in coal power plants will make this transition difficult. India is one of the major countries with significant under construction and planned increase in coal power capacity. To ascertain the likelihood and consequences of the continued expansion of coal power for India's future mitigation options, we use harmonised scenario results from national and global models along with projections from various government reports. Both these approaches estimate that coal capacity is expected to increase until 2030, along with rapid developments in wind and solar power. However, coal capacity stranding of the order of 133-237 GW needs to occur after 2030 if India were to pursue an ambitious climate policy in line with a well-below 2°C target. Earlier policy strengthening starting after 2020 can reduce stranded assets (14-159 GW) but brings with it political economy and renewable expansion challenges. We conclude that a policy limiting coal plants to those under

construction combined with higher solar targets could be politically feasible, prevent significant stranded capacity, and allow higher mitigation ambition in the future.

1 Introduction

The foremost step to reach the goals of the Paris Agreement is rapid electricity sector decarbonisation, leading eventually to a zero-emission energy supply system by mid-century (Rogelj et al., 2018, p. 129). This implies that the current global coal capacity of about 2015 GW, representing 6700 coal units and 30% of world emissions (Coal Swarm, 2019; IEA, 2018), must drop down to zero in roughly 30 years. However, up until 2018, the total coal power capacity continued to increase, even though at a decelerating pace (Shearer et al., 2019) and were the single largest contributor to the growth of energy-related emissions in 2018 (IEA, 2018). This trend might not change soon. First, because around the world, there are still 235 GW of plants under construction (India's and China's share is 15% and 55% respectively), and another 338 GW under various stages of planning (India's and China's share being 17% and 21% respectively)(Coal Swarm, 2019). Second, the operating plants in India and China, where most of the recent growth has taken place, are on an average only 12 years old and would continue to emit during their remaining lifetime[1] (see SI section 1 and Figure S3 for more information). For a budget corresponding to 1.5°C, Indian coal power plants alone are projected to use 11% of the remaining carbon budget (Supplementary Information (SI), section 3, Figure S3)

Continued investments in coal power plants and associated networks (mining and transportation) are increasing carbon lock-ins, defined in the literature as the inertia induced by fossil-related infrastructure and institutions, which reduce the prospects of alternatives to emerge and grow (Erickson et al., 2015; Unruh, 2000). In the absence of a strong climate policy, they cause extra near-term emissions, and also reduce medium to long-term mitigation potential. This strains thereby the limited carbon budget and makes long-term mitigation measures both more expensive and challenging by increasing the reliance on carbon dioxide removal technologies (Bertram et al., 2015a; Luderer et al., 2016, 2018). Consequently, to reach stringent emission reductions, modelling results show that carbon-intensive infrastructure is prematurely retired, as they become uneconomical under a high carbon price (Bertram et al., 2015a; Erickson et al., 2015; Johnson et al., 2015).. Furthermore, cost reductions in alternative power technologies, especially renewables could render

[1] Own calculation based on (Coal Swarm, 2019)

some of current investments in coal power generation stranded assets even without climate policies (Mercure et al. 2018).

The Indian power sector has evolved considerably in the last decade. The increase in installed power capacity[2] has led to drastic reductions in energy demand deficits (Central Electricity Authority, 2018a) and household electrification has reached almost 100% ("Saubhagya Dashboard," 2019). As income and population increase, the growth observed in the last decade will continue - India is projected to have the fastest growing electricity market in the world over the next decade (Tim Buckley, 2015). According to India's nationally determined contribution (NDC), "half of the India of 2030 is yet to be built". Thus, how India meets its energy demand, particularly electricity, has important implications for itself and rest of the world. As mentioned before, the path-dependence of long-lived infrastructure can reduce future flexibility, so near-term decisions are critical for a low carbon future.

After the release of India's NDC[3] and the subsequent ratification of the Paris Agreement, a number of modelling studies for India projected future energy and emissions pathways for an NDC scenario as well as other sustainable or low-carbon pathways (Byravan et al., 2017; Das and Roy, 2018; IEA, 2015; Shukla et al., 2015; Vishwanathan et al., 2018) with three of these studies specifically looking at the power sector and coal transitions in India. While many studies acknowledge path-dependence of carbon infrastructure, only Vishwanathan et al. (2018) with their national model AIM/Enduse elaborate on the issue of stranded assets in the power-sector. However, they do not quantify these assets in their scenarios. Moreover, being national models they fail to capture the influence of policies and technology developments outside their national boundaries and the achievement of the global objective of the Paris Agreement. Another recent study of Yang and Urpelainen, 2019 shows that lowering the lifespan of coal plants is the single most effective way to keep Indian emissions in line with the Paris Agreement. Although their finding illustrates the importance of carbon lock-ins/long life of energy infrastructure, their bottom-up calculations fail to capture the interactions and optimisation between different technologies in the power system which are only possible through an energy modelling or integrated assessment framework.

The objective of the paper is to understand how the path-dependency in the power sector (lock-ins) in India evolves and impacts future mitigation potential and how can they be reduced by early strengthening of policies limiting coal-based power

[2] During 2008-2018 the total utility-scale capacity increased from 166 GW to 344 GW (Central Electricity Authority, 2018a): a more than two fold increase in ten years

[3] Main features of India's (I)NDC- i) Reduction in emissions intensity of its GDP by 33 to 35 percent by 2030 (2005 reference) ii) 40% share of non-fossil capacity by 2030 iii) Additional carbon sink of 2.5 to 3 billion tonnes of CO2 equivalent through additional forest and tree cover by 2030 (not the focus of this work).

generation. A major novelty of the current work is analysing short-term mitigation options, grounding them to recent technology and policy development in India. Furthermore, this work complements earlier (mostly global) work on implications of delayed or weak near-term policies on future mitigation potential and options (Bertram et al., 2015a, 2015b; Clarke et al., 2014; Luderer et al., 2018, 2016), especially stranding of coal (Johnson et al., 2015) and how technological policies coupled with carbon pricing keep the door open for stringent mitigation (Bertram et al., 2015b), by focusing the analysis to India. The method (described in section 2) includes a model inter-comparison of harmonised scenarios comprising of national and global models.

2 Methods

The methodology of the paper essentially includes three elements: i) A harmonised set of two scenarios, called "early action" with abatement towards a global well-below 2°C goal after 2020 and "delayed action" that follows India's current policies and NDC targets until 2030 and abatement towards a global 2°C goal thereafter, ii) Implementation of these scenarios by global and national modelling teams in their respective models, and iii) Analysis of modelling results and evaluation of the near-term trends, per technology, by comparing model results with up-to-date bottom-up (national) data, existing literature and current policies.

Policy selection and implementation

A policy database, called the Climate Policy Database (CPD) was used to implement national policies into global Integrated Assessment Models (IAMs) and national energy transition models. The database collects information on currently implemented policies[4] related to climate change mitigation from countries worldwide (Climate Policy Database, 2019). Planned policies are excluded from the database, with an exception of energy and GHG (Greenhouse Gas) emission targets announced as Intended Nationally Determined Contributions (INDCs) for the post-2020 period. Policies are considered only until the end of 2016. The duration of most policies in the NDC is 2030, with a few countries (e.g. USA) being up to 2025.

From the CPD, a set of core/high-impact polices were selected for each G20 country, including India (see list in SI section 4). The selection was made with national

[4] An implemented policy is either a policy adopted by the government or a non-binding/aspirational target backed by effective policy instruments (e.g., a solar target backed up support policies like feed-in tariff, tenders etc.).

experts, with the objective of finding policies that would significantly impact GHG emissions.[5]

To be implementable in IAMs, policies were translated into policy outcome indicators, e.g. building standards were translated into final energy reductions in the building sector. Not all high-impact policies could be translated into policy indicators. For a description of how each policy indicator was implemented in each participating IAM see Roelfsema et al., 2019 (in review)

Decarbonization scenarios and scenario setup

The *Early action* scenario follows the currently implemented policies until 2020. Thereafter, it reaches for the prescribed carbon budget constraint, defined until 2100 for global models, and until 2050 for national models. While some models are cost-optimising, others simulate a carbon price, creating a response in the system that fits the carbon budgets. The global carbon budget is capped at 1000 Gt CO2 (2011-2100). Based on the latest assessment of the remaining carbon budget (Rogelj et al., 2019)[6], this figure represents more than 66% probability for a 2°C warming but less than 50% probability for a 1.5°C warming, thus falling within the definition of a well-below 2°C target. The *Delayed action* scenario consists of currently implemented policies, as before, and additional pledges mentioned in the NDC until 2030. Thereafter, like early action, delayed action includes the carbon budget constraint, with both scenarios have the same carbon budget. However, unlike the global models, the two national models (AIM/Enduse and India MARKAL) have different targets, both of which are above the 2011-2050 budget observed for India in the global early action 2°C scenarios. India MARKAL assumes a much higher GDP growth rate (see SI section 8) than AIM/Enduse and doesn't include CCS (carbon capture and storage), which leads to much higher baselines emissions and constrains how much decarbonization is possible. Furthermore, the scenario setup differs for national and global models and is shown in Table 1. For a detailed methodology see SI section 5.

[5] See Work Package 2 of the CD-LINKS project for detailed information on how policies were selected at http://www.cd-links.org/?page_id=620.

[6] For the period 2011-2100, the remaining carbon budget for a 1.5°C target is 770 Gt CO2 and 510 Gt CO2 with 50% and 66 % probability respectively. For 2°C, these numbers are 1690 and 1360 Gt CO2. Assuming emissions from 2011-2018 to be 290 Gt CO2. Not including feedback effects from permafrost thaw.

Scenario name	Description	National Models	Global Models
Early action	Currently implemented climate and energy policies till 2020 followed by a carbon budget constraint till 2050/2100.	Budgets represent the mitigation effort, till 2050, possible through each model. The budget, until 2050, is 136 Gt CO2 for AIM/Enduse and 191 Gt CO2 for India MARKAL.[7]	Same global carbon budget across all models (2011-2100 of 1000 Gt CO2 for total CO2 emissions including anthropogenic land-use)
Delayed action	Currently implemented climate and energy policies and NDC till 2030 followed by carbon budget constraint till 2050/2100, without anticipation of the constraint prior to 2030.		

Table 1 Summary of scenario setup used in this paper. There are two scenarios – Early action and Delayed action. Two national models and six global models have been used in the analysis.

Models

The models used in this study include six global Integrated Assessment Models (IAMs), which help in exploring interactions between the economy, land, and the energy system. They tend to be quite broad and include stylized and simplified representations of these subsystems (Rogelj et al., 2018). These are: AIM V2.1, REMIND-MAgPIE, WITCH, IMAGE, GEM-E3 and POLES. Furthermore, two national energy system models are used - India MARKAL and AIM/Enduse (see SI section 6 for a description of each model).

Global models include inter-regional trade, the pace and cost dynamics of new technologies, and the link between the global economy with the global climate

[7] The early and delay budgets are slightly different (see Table S3 in the SI). These budgets refer to CO2 from energy use and industry only.

system. Most of them are technology rich, giving the energy system a variety of decarbonization options. On the other hand, national models can generally consider national circumstances and constraints in more detail.

The models have different structural representations of the energy system and solution paradigms and differ significantly in their assumptions and implementation of policies[8]. The diversity of modelling approaches and assumptions reflect the inherent uncertainty about drivers and determinants of social systems, and the comparison of results allows for identification of robust and sensitive effects. For an overview of techno-economic assumptions used by the suite of models, refer to (Krey et al., 2019) and for a comparison of key socio-economic assumptions like GDP, Population, and Energy demand across the models, see SI section 8.

The modelling of energy storage and batteries is crucial to high shares of VRE in the energy mix. How these are modelled for each of the models is given in Table S9 in the SI section 14. In general, storage requirements increase with increasing share of variable renewables and require additional investment which leads to increasing levelized cost of electricity (Pietzcker et al., 2017; Ueckerdt et al., 2017).

Bottom-up evaluation

As the energy sector is changing fast and transformative changes are required to drastically reduce emissions, evaluation through bottom-up data allows to put scenario results into the context of current developments. These are especially relevant for the first future years of the modelling which typically takes place in 5-year time steps. We evaluate the near-term feasibility of these pathways by looking in-depth at what plagues or enriches each technological option in the power sector in India. More information about the bottom-up sources, namely the Central Electricity Authority's (CEA) National Electricity Plan (NEP) and Coal Swarm's "EndCoal" database is available in the SI (section 2).

3 Results

3.1 Near-term trends under the NDCs

[8] Unlike REMIND, WITCH, AIM and GEM-E3 which perform some form of cost-optimization in their models (see SI section 6 for details) POLES and IMAGE are not cost-optimization models but simulation models. Carbon prices are used to create a response in the system that fits the budgets, but no optimality is sought.

Coal expansion till 2030

Pledges under the NDC take into effect during the period 2020-2030. Under India's NDC, models project coal-based[9] generation to increase relative to current generation, although there is a wide-spread (1158-2025 TWh in 2030 for global models in grey ribbon with upper limit until 2764 TWh when including all models, Figure 1). One outlier to this result is the national model AIM/Enduse which projects a decrease in coal-based generation from 2020 onwards. It projects this transition by rapid expansion of natural gas-fired generation and CCS (Carbon capture and storage) and overall lower demand growth (See SI sections 7 and 8 for more information). The bottom-up projections from CEA, in black triangles, also show an increase and fall within the range of model results. Thus, both the modelling results and bottom-up projections show that under currently implemented policies and NDC pledges coal-based power generation likely continues to increase in India. This is consistent with India's NDC, which states that *"coal will continue to dominate power generation in future"* and Coal India Limited, provider of over 80% of domestic coal, significantly increasing investment in exploiting the country's coal reserves (Press Trust of India, 2019a). To provide further context, results from two other national modelling studies have been included – the NITI Aayog's India Energy Security Scenarios (IESS)[10] and the NITI Aayog – India Energy Model (Thambi et al., 2017), both falling well within the range of model results

Recent developments in the coal sector indicate that the periods of high capacity additions are over. The number of cancelled plants is increasing and those of planned plants decreasing (Figure S1 in SI). In 2018-19, the capacity addition fell to a record low of 3.6 GW (Asian News International, 2019) (compared to an average of 10 GW per year additions during 2015- 2018) and some of the major power developers have vowed to move away from coal (Press Trust of India, 2019b). One reason for this slowdown is the over-capacity in power generation which has led to around 40 GW of "stressed" coal capacity[11] and many plants running at well-below their operating capacities (see SI section 12 for discussion on its drivers).

Thus, although there might be a reduction in the pace of addition of coal-based power generation in the coming years, the overall generation would likely continue to increase.

[9] Throughout the text, the word "coal" implies "coal without CCS", unless otherwise stated.

[10] http://www.iess2047.gov.in. The IESS Scenarios don't include an explicitly called NDC scenario. They include a range of scenarios with the closest to an NDC scenario being the L2 or "Determined Effort " scenario (Jain, 2015).

[11] Stressed assets are those accounts where there has been either been a delay or potential for delay, in payment of interest/principal by a stipulated date, as against the repayment schedule (Standing Committee on Energy, 2018)

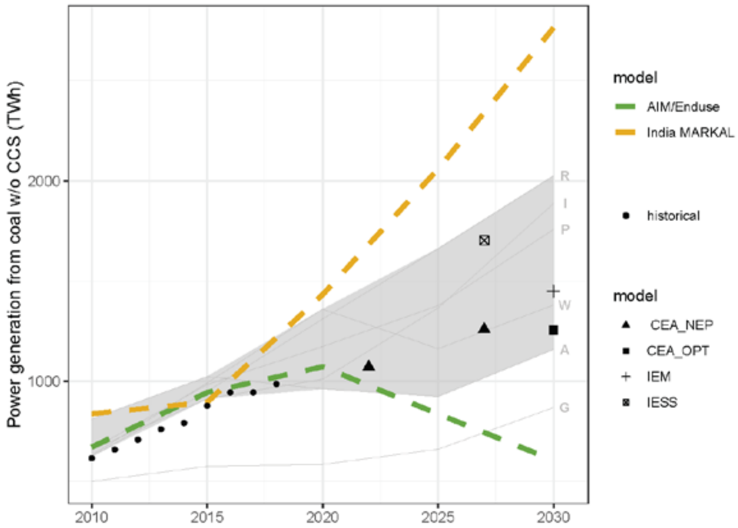


Figure 1: Power generation from Coal (2010 to 2030 in TWh) for the delayed scenario. The grey ribbon represents the spread from the global models (except GEM-E3, see SI section 7). The alphabets represent the first letter of the name of each global model. The coloured-dashed lines are the national models. The black circles are historical values, black triangles (projections) are projections from CEA NEP, and black square is the projection from the CEA "Optimal Generation Growth" report (Central Electricity Authority, 2019). All bottom-up reports represent only utility-scale generation. The cross and the cross in the square are projections from two other studies, the IEM and IESS respectively.

Solar and Wind expansion

In 2015, the target for solar under India's solar mission was increased five-fold from 20 GW to 100 GW (India's NDC, 2015) in 2022. This also became part of a target of 175 GW of renewable energy (excluding large hydro (>25 MW)) by 2022. Additionally, in its National Electricity Plan, the CEA projects an addition of 50 GW solar and 40 GW wind during the period 2022-2027 to achieve 275 GW of renewable capacity in 2027 (black triangles in Figure 2). Solar capacity has exponentially grown over the last five years (the current capacity[12] is 28 GW for solar and 35 GW for wind - see SI section 2). Even without a carbon price[13], new solar has become competitive to new coal and two-thirds of the existing coal power plants (Greenpeace, 2017; Oliver, 2018)

Figure 2a, for solar, shows that, in 2030, the national (270 - 380 TWh) and global (192-455 TWh) models are broadly in line with the projections (243 TWh in 2027) from the CEA. The results are similar for wind (Figure 2b) with national (117-334 TWh) and

[12] As of March 2019. For capacity additions and absolute capacities of different technologies from CEA National Electricity Plan, see SI, section 2, Table S1.

[13] India's current coal cess renamed 'Clean Environment Cess' is Rs. 400/ton (USD6/ton) (levied on coal, peat, and lignite) ("Budget 2016-2017 Speech of Arun Jaitley, Minister of Finance," 2016) ~USD 1.6/ton CO2, can be labelled as a carbon tax, but is considered insignificant for our purposes.

global (151-312 TWh) projections broadly in line with projections from CEA (188 TWh in 2027).

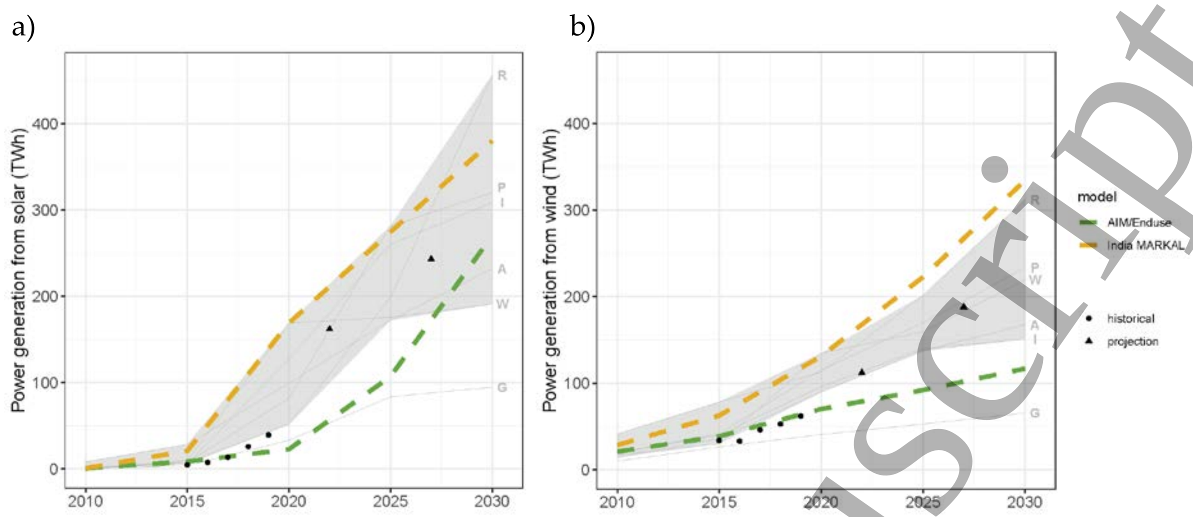


Figure 2: Power generation from (a) solar (a) and wind for the delayed scenario until 2030. The black dots represent historical values and the black triangles are projections from the CEA NEP. The latter include renewable targets mentioned in the NDC (175 GW of installed renewable capacity by 2022) and additionally, renewable energy projections from 2022-2027 (installed renewable capacity of 275 GW by 2027), which are however not part of the NDC. The grey ribbon shows the spread of the global IAMs, the coloured-dashed lines are the national models.

Near-term projection of coal alternatives – gas

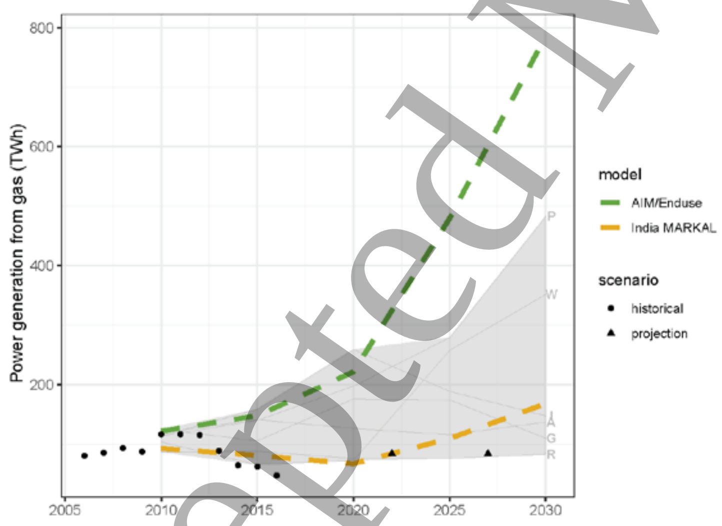


Figure 3 Power generation from gas (TWh) from 2005-2030. Black dots are historical values and black triangles are projections from CEA. The grey ribbon represents the range across the global IAMs while the dashed coloured lines are the national models.

In the energy transformation pathways for many regions of the world, gas is the most important alternative to coal in the near-term. Secondly, gas provides peak capacity, increasing the flexibility of the power system as more renewables are integrated.

Compared to projections from CEA, many models project significant near-term increase in gas-based generation under current policies (Figure 3). However, several factors make this scenario unlikely for India.

Low supply of domestic gas and high prices of imported LNG (Liquefied Natural Gas) have left around 50% or 14 GW of the plants stranded; the current PLF (plant load factor) of gas plants is 25% (Central Electricity Authority, 2018b). Secondly, gas for power plants competes with other uses, which are given a higher priority (Standing Committee on Energy, 2019). These include cooking (as PNG or Piped Natural Gas and LPG or Liquefied Petroleum Gas), as CNG (Compressed Natural Gas) in the transportation sector, and the fertiliser sector (as raw material) [14].

The construction of the long-distance TAPI (Turkmenistan-Afghanistan-Pakistan-India) pipeline woud eventually[15] supply India with more gas (almost half of the current domestic production of 32 billion cubic metres). However, as mentioned before, power generation competes with other uses and as the pipeline connectivity within the country improves (Ministry of Petroleum & Natural Gas, 2015), the demand in these high-priority sectors will also increase. Under these circumstances gas power plants are unlikely to receive a dominant share of the incoming gas.

Thus, unless there is a further decrease in international gas prices and subsequent ramp-up of LNG terminals or exploration and ramp-up of shale-gas production, gas is unlikely to play a significant role in near-term power production in India (Chaturvedi et al., 2018; Sen, 2015).

Other technologies

Most models project modest increases in nuclear and hydropower generation in India; also reflected in projections by the CEA. See SI section 11 for model projections of these technologies in context to their policy and technological development.

3.2 Early vs. Delayed action

In the delayed action scenario, the power system follows the NDC trajectory until 2030 (as presented in 3.1). Thereafter, the global IAMs achieve cost-effective mitigation (through a carbon price) under a carbon budget constraint up to 2100. On

[14] Uses not mentioned here include steel, refineries & petrochemicals

[15] The construction of the 1814 km long pipeline started in 2015 and was projected to become operational by the end of 2019 (http://www.oilgas.gov.tm/en/blog/124/the-office-of-consortium-galkynysh--tapi-pipeline-company-limited-will-be-opened-in-dubai). However, considering that the pipeline must pass route through sensitive socio-politic regions, the project might face significant delays.

the other hand, an "immediate or early action" scenario introduces a carbon price already after 2020. The difference between the two scenarios can shed light on the path-dependency of near-term actions. The concept of carbon lock-ins suggests that near-term addition of carbon infrastructure makes stringent mitigation targets more difficult and costlier to achieve - by prohibiting alternatives to emerge and wasting investments through premature retirement and stranded assets. The rest of the section will show key differences between these two scenarios.

Stranded capacity

Under a climate policy based on carbon pricing, the carbon price increases with time. Such a policy forces power plant operators to run their plants at a load factor well-below its optimal design to reduce operating costs. Furthermore, if the load factor falls below a certain point, the coal plant cannot recover fixed and variable operational costs leading to premature retirement, i.e., before its expected lifetime, and the plant is said to be stranded. However, such a chain of real-life decisions are not represented in models because of their inability to include single power plants and track their age over time. We thus use an illustrative way to calculate stranded capacity, which is uniform across models (See SI, section 10 for details).

Figure 4 illustrates four aspects - 1) Figure 4a and 4b show coal capacity as it retires naturally[16] (dark blue line), starting in 2020 (early action) and 2030 (delayed action). The bars represent coal capacity and are color-coded according to the age-group of the plants in each year. How the plants are tracked over time is explained in detail in the SI section 10 but an illustration is provided in Figure 4c on how vintages are calculated); 2) The black lines are the early and delayed mitigation pathways compatible with the Paris Agreement (with the global model REMIND as example), 3) The stranded capacity is represented by the region above the black line (as an example in Figure 4a the purple line depicts stranded capacity, for the years 2030 and 2040 in early action). For both - the early and the delayed scenario in REMIND, roughly all plants older than 20 years are retired, but the magnitude of stranded capacity is higher in delayed action (~300 GW vs ~150 GW in early action in 2050); 4) The Total stranded capacity (polygonal area) in the delay scenario (Figure 4b) – shows that the magnitude of stranded capacity from plants yet to be built and currently installed plants would be similar.

[16] Capacities have been derived from Secondary Electricity, assuming a constant capacity factor of 0.59. See SI section 10 for more information.

Results for the other models are presented in SI section 10 but main results are given below.

a)

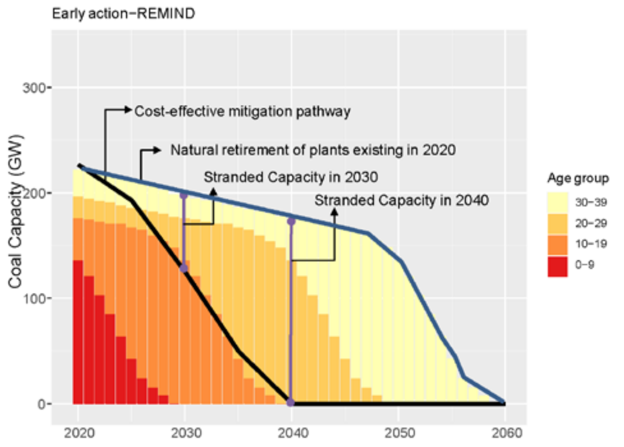
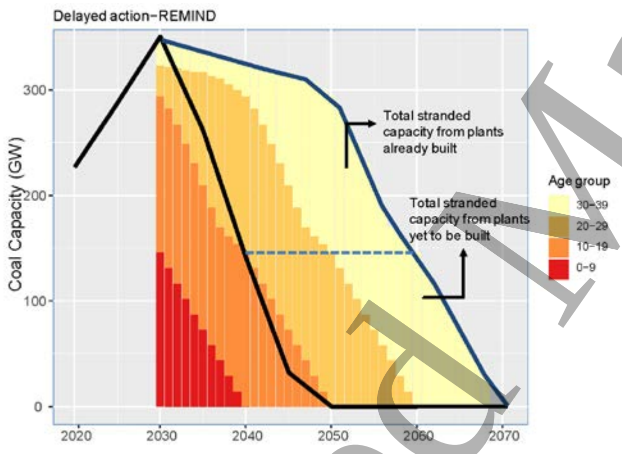


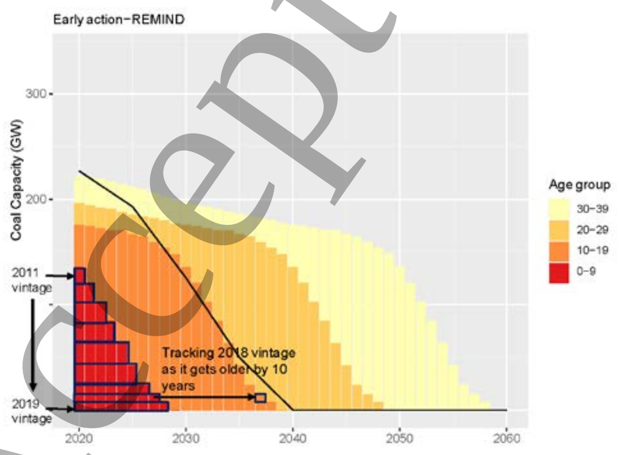
Figure 4 Coal capacity development assuming natural retirement (dark blue line) and coloured according to age-group. Black lines are cost-effective pathways (calculated from the generation data, see SI section 10 for an explanation. Results for a) Early action and b) Delayed action for REMIND. Results for other models are presented in SI Figure S14. Purple lines in a) are used to illustrate stranded capacity, while the dotted light blue-line in b) divides the total stranded capacity from plants already built and yet to be built.

b)



c) Explanation of how vintages are calculated. The arrow indicates that the "2018 vintage" in the 0-9 age bracket in 2027 becomes 10 years older in 2037 and shifts to the 10-19 age group. The size of historic vintages is taken calculated from the age pf each power plant provided in (Coal Swarm, 2019), and for the delay scenario (not shown here), equal additions between 2020 and 2030 are assumed, deduced from total capacity increase in the respective scenarios and shown in Table S6

c)



The range of stranded capacity in the period from 2030 to 2050 across models for Delayed action is 133-227 GW and for Early action, over the 2020 to 2050 period, 14-159 GW (SI section 10, Table S7). In general, although delayed action leads to higher total stranded capacity, early action leads to slightly higher stranding of younger plants (in the age group of 11-20 years), (SI, section 10, Table S7 for details). This is because today's plants, most of which are quite young, are stopped almost immediately in the early action scenario.

Thus, in scenarios where a carbon price is enacted early, the amount of stranded capacity is reduced but not eliminated. Importantly, however, in the early scenario, only already existing plants become stranded, many of which have been planned and constructed without anticipation of the Paris Agreement or of the cost reductions seen for crucial decarbonisation technologies like solar, wind, and battery storage. In the delay scenario, a sizeable share of stranding is from plants yet to be built (see bottom right in Figure 4, panel b).

Solar and Wind potential

Early action scenarios introduce stringent climate policy in the form of a carbon price. A higher carbon price makes fossil fuels more expensive and incentivises alternatives to emerge (see SI section 9 for a carbon price comparison across models). In 2030, the delayed action scenario has no carbon price.

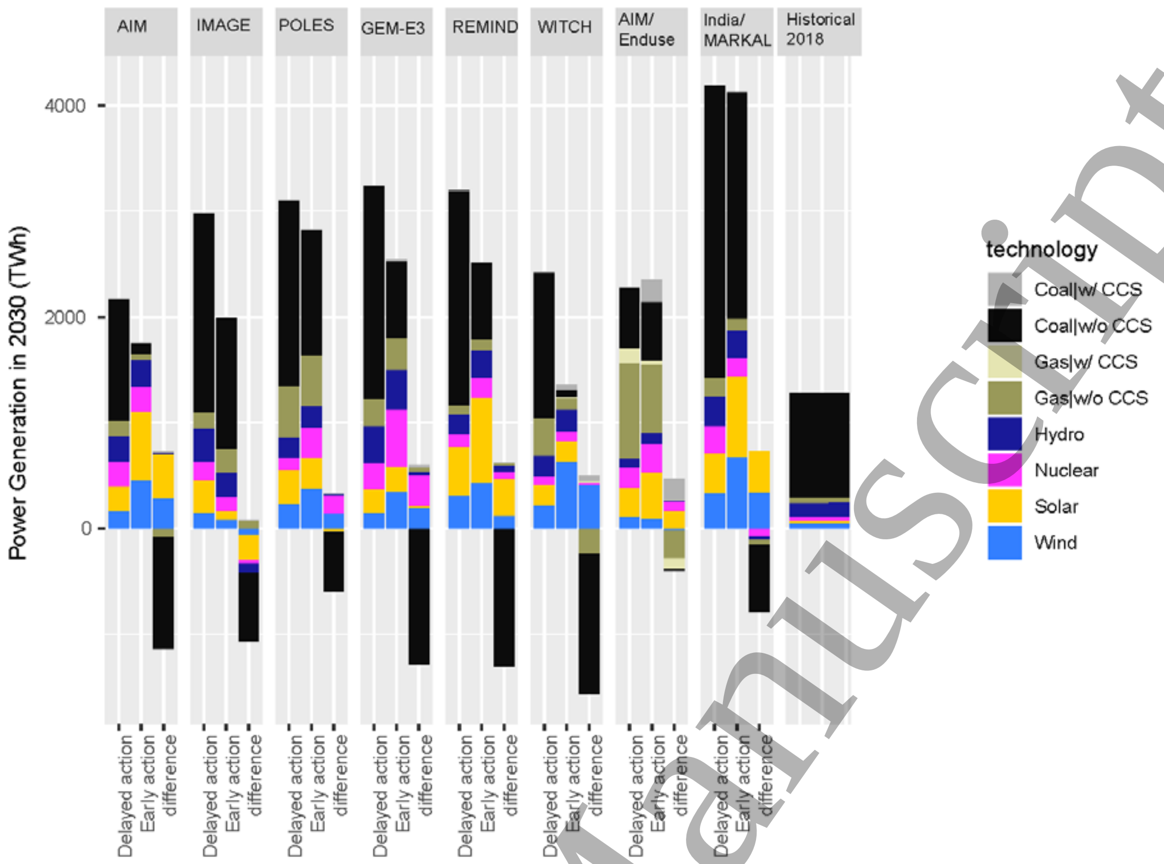


Figure 5 Power generation in 2030 from different sources for the two scenarios - Delayed and Early action, as well as the difference of the two scenarios. The distribution of power from different sources in 2018 is shown in the extreme right column.

In early action scenarios, more renewable energy and nuclear is added to the power system (see Figure 5, except IMAGE- see discussion in SI Section 7), while reducing coal power need by 557-1320 TWh (see "difference" in 2030, excluding AIM/Enduse). Thus, given the option to start mitigation earlier, many models decide not to build coal (SI Figure S10). Although the long-term (2050) final power demand across models doesn't differ significantly in the two scenarios (SI figure S4), for the global IAMs, the demand dips following the introduction of a carbon price (visible by the sum of the bars in Figure 5). For this reason, not all coal is replaced by renewables in the delayed action. Lower electricity demand in the early action leads to lower generation requirements in the near-term. This is in contrast with the much lower elasticity of national models, where electricity demand in the near-term is almost unaffected across the two scenarios.

Importantly, IAMs and national models project that, under a constrained carbon budget, an even more rapid scale-up of (primarily) solar and wind compared to early action (Figure 2) is cost-efficient.

4 Discussion

In the previous section, we showed the development of key technologies under NDC until 2030 and commented on their plausibility using policy developments and circumstances unique to India. This was followed by comparison of mitigation action between early and delay scenarios, showing the potentials and challenges of different technologies for decarbonisation. It is worth mentioning that although each model assess the Paris-compatible pathway differently, most consider an internationally economically-optimal (or least cost) pathway to reach the target. Such an approach has obvious equity implications – considering the development statuses and historic responsibility of each nation. However, addressing those is beyond the scope of the study.

4.1 Potential for solar and wind expansion

Coal-fired power plants planned for the next decade would constitute a significant share of stranded capacity under a climate policy compatible with the Paris Agreement (Figure 4). Avoiding this requires further investment in solar and wind. There are some indications that India might actually raise its solar and wind targets to 300 GW and 140 GW respectively (Central Electricity Authority, 2019; Reuters, 2019), from the 150 GW and 100 GW (solar and wind respectively) in 2027 included in the NEP. Thus, such an ambition would be a step towards decarbonizing the power system. However, increasing coal generation (aided by the absence of an explicit policy limiting coal generation) and with increasing penetration of variable renewable energy (VRE) in the power system, new coal generators could face low or falling load factors (Chaturvedi et al., 2018; Hirth et al., 2015; Palchak et al., 2017; Scholz et al., 2017), exacerbating the current stressed assets in the sector. At the same time, although it might be "economically" rational to lower coal power PLF under such a scenario (especially for newer coal plants with higher tariffs), political economy factors surrounding coal power and electricity pricing in India could mean that VRE is curtailed in spite of its must-run status. Curtailment is already a serious issue for VRE investments in Andhra Pradesh and Tamil Nadu (Jawar, 2020) .

4.2 Scenarios of coal capacity development in India

The sections before highlighted the policies and targets in place for renewable technologies and outlined the current situation of the coal power sector - one reeling under low plant load factors and many stressed assets. Taking these, and other literature studies into account, this section explores the various trajectories of coal capacity development in India and their implications.

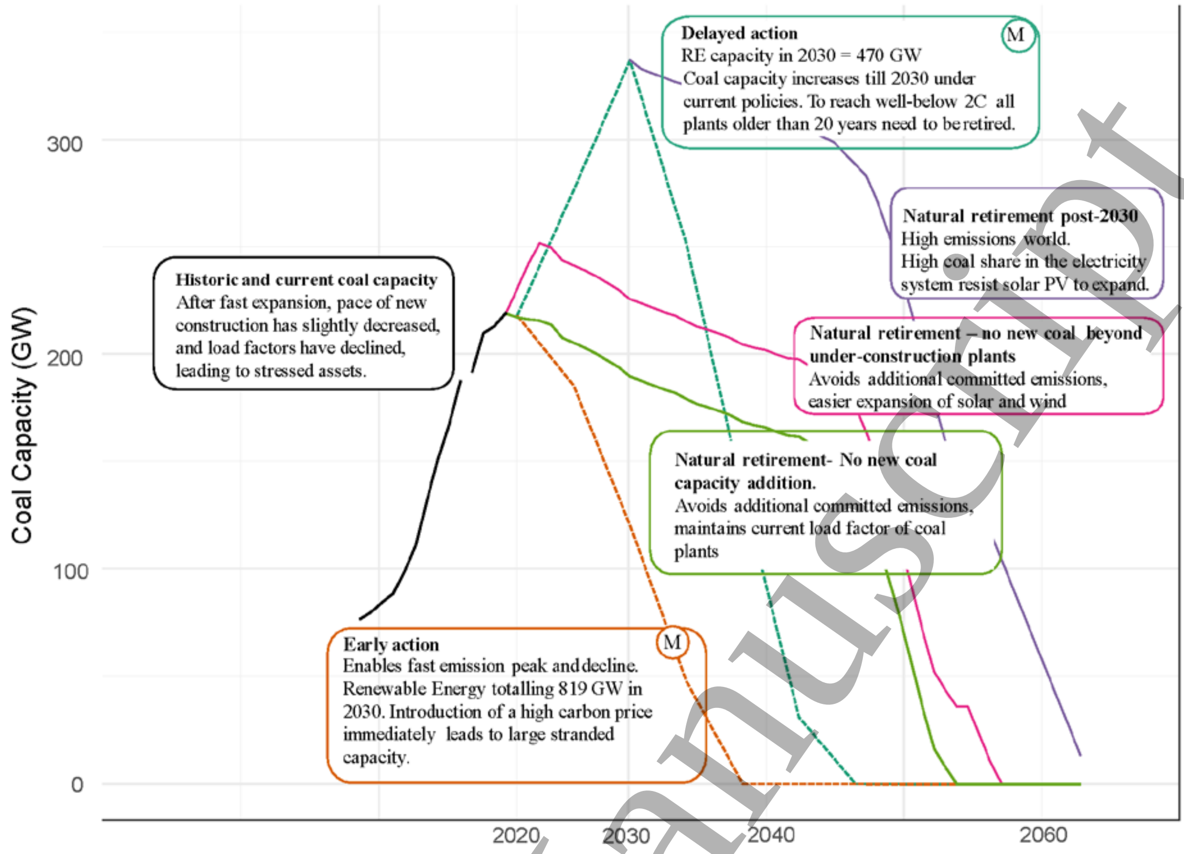


Figure 6 Descriptions and implications of various scenarios of coal capacity development in India. "M" denotes modelling result, the example shown is from the global model REMIND. The Purple line is deduced from the 2030 generation value in REMIND, while the green and purple are based on bottom-up data.

In 2015, a new legislation was introduced requiring all coal power plants to control the concentration of certain pollutants (Central Electricity Authority, 2018b). In general, the implementation of this legislation will significantly reduce the share of power plants in total SO2, NOx and PM2.5 emissions (Purohit et al., 2019), thereby reducing the possibility of them being prematurely shutdown due to air pollution concerns. However, uncertainty arises due to the heavily regularised and politicised nature of the electricity sector and the location of certain plants close to large cities (see SI section 14 for details).

Both the early and delay action scenarios (orange and green dashed lines- figure 6) consider the implementation of a high carbon price which gradually increases over time (SI Section 9). Such high carbon prices could result in disruptive changes and financial instability (Campiglio et al., 2018; Kriegler et al., 2018) - as also shown by the large amounts of stranded capacity (SI section 10). Therefore, such a policy would be especially avoided by risk-averse policy makers in a growing but still developing country like India. Secondly, although carbon pricing is the principle policy instrument used in IAMs to mitigate emissions, previous studies have shown that policy makers favour to implement a mix of multiple, overlapping instruments over carbon prices to achieve climate mitigation (Jenkins, 2014); often starting with the power sector (*Renewables Global Status Report*, 2019). Such policies are not only more politically feasible to implement but give rise to coalitions and constituencies supporting low-carbon transformation, essential in the political economy of decarbonization (Meckling et al., 2017).

The purple line represents a continuation of coal capacity growth as projected till 2030 and a natural decline thereafter, and thus shows the risks of what the continuation of NDC policy ambition until 2030 entails. Under such a scenario, coal power in India alone would take up ~11 % of the global carbon budget for a 1.5C target (see SI section 3).

Thus, a more politically feasible pathway in the short-term and an intermediate between the two policy scenarios is represented by the spectrum spanned by the green and purple lines. Here, no coal additions take place (beyond plants under-construction in turquoise) and the coal plants run till the end of their lifetime. Such a policy ("coal moratorium" in (Bertram et al., 2015a) will bring additional benefits – keeping the plant load factor of existing coal plants at the current level, preventing the power system to get further locked into coal and thus necessitating large stranded assets in the future, opening the possibility of integrating emerging and cheaper power technologies in the future, and as mentioned before - laying down important groundwork for ambitious future climate policy. However, such a policy would necessitate a moderate increase in power from other sources, but at a reduced rate compared to the "Early action" scenario. As presented in preceding sections, Solar PV and Wind could take the bulk of the additional electricity demand.

4.3 Limitations

The study quantifies the stranded coal power capacity in India in the context of declining costs of renewables, especially solar, long life of coal power plants, and policies in line with the Paris Agreement. However, a number of other factors could influence the stranded capacity of coal generators, which have been either partially considered or absent in this study.

The study does not explore specific environmental constraints like water-use in coal power plants, which will become increasingly relevant for India (Caldecott, 2015; Manthan India, 2017; Tang et al., 2019; Vishwanathan et al., 2018), nor includes local environmental damages from mining (Worrall et al., 2019). Other factors unique to India which affect the operation of coal generators, like the severe debt of distribution companies and implicit and explicit subsidies to coal (Worrall et al., 2019) have also not been considered.

Other limitations include inherent methodological challenges – like the inability to run at hourly timescales (which is important to explore grid and plant flexibility at high VRE penetration rates), although models use various approaches to represent integration challenges of VRE in the grid ((Pietzcker et al., 2017), further information in SI section 14). Furthermore, how higher shares of VRE in the grid could exacerbate stressed assets in the power section and lead to stranding has only be mentioned qualitatively.

5 Conclusions

The study shows that avoiding and minimizing the stranding of coal power plants in India in a low carbon world require support for alternative power system solutions and the need for an early definitive policy on coal-based power generation. An example of such a policy could be forbidding any new coal power (with possible exception of those already under construction) and simultaneously phasing out old, inefficient plants. While the government's energy policies have actively supported alternate power, the latter are missing in the portfolio. Such a policy would also allow for stabilizing the capacity factors (full-load hours) of existing plants. Importantly, it would prevent India from further falling into a carbon lock-in leading to stranded assets and provide the possibility for future ambitious mitigation.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642147 (CD-LINKS).

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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