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Solar energy as an early just transition opportunity for coal-bearing states in India

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Abstract

Continued investment in coal embroils regions in coal lock-ins, creating dependence and vested interests around coal and thereby limiting the speed and potential to switch to cleaner energy. In India, four states contribute 70% of coal production, with regions surrounding mines also housing significant operating and under-construction coal power stations. On the other hand, states in the west and south of India dominate current and near-term renewable energy capacity growth, broadly following patterns of highest resource potentials. We show that following current policies, by the end of the decade, coal-bearing states will likely sink deeper into carbon lock-ins, while the rest of the country, especially western and southern states could become increasingly decarbonised. Even in decarbonisation scenarios, gains from job and value creation in the clean energy sector might primarily take place away from existing coal regions, raising equity concerns, and ultimately putting the political feasibility of such a scenario in question. We suggest that policies aiming at higher renewable installations (mostly solar due to better potentials) in coal-bearing states, although not a one-to-one panacea, could provide an early break from lock-ins and into a just transition. This may, however, require a dedicated program and imply a small mark-up in power system costs. They would, however, help for medium-term diversification and job creation in all regions which will be key for assuring political support for the transition.

1. Introduction

The decarbonisation of India's power sector is slowly underway. Based on the government's renewable energy (RE) policies and targets until 2030, the Central Electricity Authority projects that by 2030, the share of non-fossil capacity would reach 64% (Central Electricity Authority 2020a), from 38.5% today (Ministry of Power 2021) mainly from solar and wind. Despite these optimistic projections, experience of policymaking in other countries and studies investigating the historical diffusion of technologies have shown that there can be significant political and institutional constraints to decarbonisation. For example, continued near-term investment in fossil fuels could strengthen carbon lock-ins, defined as a path dependence on fossil fuels which through interdependencies in institutional and political spheres, long infrastructure lifetimes, and reinforcing action, could hinder a transition to alternative energy (Unruh 2000, Seto *et al* 2016). Furthermore, the energy transition would also lead to loss of employment and employment opportunities for people directly or indirectly related to fossil fuels or living in regions with significant fossil resources as well as those who spend significant income in acquiring energy. Without adequate compensation or alternate opportunities, these groups or individuals could also hinder decarbonisation (Healy and Barry 2017, McCauley and Heffron 2018).

In India, coal mining is firmly located in the country's east—with four states controlling ∼77% of the share: Chhattisgarh (22.2%), Odisha (19.8%), Jharkhand (18.5%), and Madhya Pradesh (16.3%) in 2018–2019 (Coal Controller's Organisation 2019) (see figure 3, coal mines in red). Coal power plants are more uniformly spread, although still concentrated around coal mines (figure 3—right panel). The political economy of coal is driven largely by the state and central government: 80% of the total mined coal (through Coal India Limited) and 62% of all coal power plants are government owned[1] (Ministry of Coal 2019, Central Electricity Authority 2020b). This has created vested interests at all levels of government and along the value chain, especially in coal-bearing regions where mining and associated activities not only provide important employment opportunities and contribute to regional economic development but also personally benefit local politicians (Chandra 2018, Montrone *et al* 2021).

The concept of just transition is that people, communities, and regions who stand to lose the most from an energy transition undergo an inclusive and planned shift to alternate means of income and sustenance or get adequate compensation (Newell and Mulvaney 2013, Jasanoff 2018, Bhushan *et al* 2020, Prayas and CPR 2020). To a lesser extent, it also implies that the benefits from a transition, in the form of additional jobs created in the renewable supply chain, better air (through cleaner power), or cheaper power are also not concentrated in certain regions. Just transition has thus important political salience for decarbonisation policies.

There are two main objectives of this paper: (a) to argue for a just transition or transition planning in coal-bearing states of India, and (b) to explore the role of solar energy in that transition; both through the lens of (energy) employment. In doing so, we build on existing literature of just transition in developing countries like India, by adding nuanced technological and sub-national perspectives to the discussion. For example, while Pai *et al* (2020) ascertain the geospatial potential of replacing coal mining jobs with long-term solar and wind energy jobs, they use a dichotomic view of estimating techno-economic suitability, i.e. above or below a given threshold (e.g. solar irradiance), thereby masking other factors affecting RE deployment, e.g. capacity factors and resource potentials. Furthermore, any discussion on just transition needs to be embedded in country-specific energy scenarios, i.e. view just transition within a wider country-wide discussion on energy transition.

2. Methodology

2.1. Energy employment model and energy scenarios

Energy employment estimates for different technologies and activities are calculated from an employment model based on the employment-factor approach, whose methodology and assumptions are described in Malik *et al* (2021). The model builds on previous employment factor work by Rutovitz *et al* (2015); Rutovitz and Harris (2012); Rutovitz and Atherton (2009), and uses updated employment factor estimates for Europe and India. It works in ex-post mode and can take energy-related results from any energy model or integrated assessment model (IAM) as input. It differentiates between various technologies and fuels, and further estimates different job types along the value chain from manufacturing, construction and installation (C&I) to operation and maintenance (O&M) (and fuel supply for combustible fuel technologies). The output of the model is direct energy jobs for each technology and value-chain for each time step. Major assumptions include how the employment factor (defined as the number of jobs resulting from a unit investment or unit production of a physical commodity) evolves into the future, the share of local manufacture (only for solar and wind energy) and its evolution, and the share of sub-technologies like solar rooftop and wind offshore because the IAM used only includes a generic representation of these technologies. For the current study, the open-source global IAM REMIND version 2.1 (Baumstark *et al* 2021) was used to run two policy scenarios 'NDC' and '1.5 °C' (also called 'Pol' in the paper) (described in table 1, also used in Malik *et al* 2021). The model REMIND combines the global energy–economy–emissions system and explores transformation pathways subject to welfare maximisation under perfect foresight and 'climate and sustainability constraints for the time horizon 2005 to 2100' (Baumstark *et al* 2021). It includes 12 aggregated regions (the resolution and the aggregation of regions can be changed), a detailed representation of the energy sector, and 'fully accounts for interregional trade in goods, (and) energy carriers'.

2.2. Power-plant location data, resource potentials, and capacity factors

The study uses locations of operating, under-construction, and planned power projects and mines in India. The procedure to collect this data, including their accurateness, is available in the SI sections 1 and 2 (available online at stacks.iop.org/ERL/17/034011/mmedia). The underlying data, including the code for the figures, is freely available in Malik and Bertram (2022).

The resource potentials and capacity factors for solar have been calculated using the tool 'REexplorer' from the National Renewable Energy Laboratory (www.re-explorer.org/about.html). The tool allows a user to set constraints on allowed land-use types, as well as provide inputs of power density, type of solar PV, etc. The methodology, including the sensitivity of the potentials to different land constraints, has been provided in the SI section 3. The resource potential for wind has been used from an existing study done by the National Institute of Wind Energy at 120 m height (National Institute of Wind Energy 2019).

[1] Includes both state and central government.

Table 1. Description of scenarios used in the paper.

Scenario name	Scenario description
NDC	Reaches NDC targets (as submitted to the United Nations Framework Convention on Climate Change until 2019, a rather conservative policy scenario as new neutrality pledges and 2030 targets announced by EU, China, Japan, and others are not considered) in 2030 via regionally differentiated, iteratively adjusted carbon prices, and assuming gradual convergence to average carbon prices thereafter. For India, the non-fossil share of power capacity (40% by 2030) and the reduction in carbon intensity of its GDP by 33%–35% by 2030 (2005 reference) are represented.
1.5 °C ('Pol')	Immediate introduction of regionally differentiated carbon prices which converge in 2050, iteratively adjusted to fulfil a constraint in carbon budget (900 $GtCO_2$) from 2011 to time of net-zero global CO_2 emissions. Carbon prices after reaching net-zero increase moderately, leading to moderate net-negative emissions thereafter, and a 66% chance of limiting temperature increase below 1.5 °C at the end of the century (2100).

3. Results

3.1. Near and long-term changes in total energy employment across India for two policy scenarios

In 2020, the total direct energy supply jobs in India were around 1.5 million; almost two-thirds of them in the fossil sector, and the rest one-third in the non-fossil sector (figure 1(a)). Coal, by far, dominates these jobs (∼800 000; grey), followed by biomass (∼290 000; green), and hydropower and solar PV (∼100 000 each; dark blue and yellow respectively) (figures 1(b) and (c)). Within coal jobs, almost 385 000 people are directly employed in resource extraction, followed by the manufacturing of equipment used in coal power ∼200 000 (figure 1(c); purple and rust yellow). Furthermore, fuel supply (extraction) constitutes the largest share (∼43%) of the current total energy supply jobs (figure 1(c); purple).

In the NDC scenario (figures 1(a) and (b)), total energy jobs increase slightly during the next 5 years, until 2025, and then fall back to almost the current level in 2030. This is mainly because of the evolution of jobs in coal. Although there is a significant addition of coal production and coal power until 2030 (SI, figures S3(b) and (c)), the increasing labour productivity in both these activities coupled with the drying up of new construction projects after 2030, leads fossil jobs to be initially stable but then decline until 2030 (figure 2(b)). On the other hand, in the non-fossil sector, the decrease is primarily in the biomass sector, also due to the massive productivity gains in fuel production. Job additions take place primarily in solar and wind energy (figure 2(b)); mostly in the O&M and C&I activities; local manufacturing jobs, starting from a low base, increase but only modestly.

In the 1.5 °C ('Pol') policy scenario, an even higher number of jobs (∼500 000) are lost in the next decade, mainly due to a reduction in manufacturing jobs of coal equipment and extraction jobs in coal mining (figure 2(b)). However, this decrease is compensated by an almost equal number of jobs created in solar and wind energy (figure 2(b)). Here, jobs are created mostly in the O&M of running capacity and the C&I of new capacity (figure 2(b)).

In both the scenarios of weak (NDC) and stringent (Pol) mitigation, the total jobs in 2030 are roughly equal, which in turn are similar to total job numbers in 2020 (figure 1(a)). The primary difference between the two arises post-2030—employment in the stringent mitigation scenario increases steadily (until 2050) due to the significant addition of new solar and wind capacity. This happens despite the increasing labour productivity in these technologies and decreasing employment in fossils. Although the manufacturing of these technologies is assumed to become completely local by 2050, manufacturing jobs constitute a small share of the total jobs; the majority being in O&M and C&I. In comparison, direct energy jobs in the NDC scenario decrease for a few decades before picking up post-2040 due to (delayed) installation of solar and wind energy.

Thus, while a stringent mitigation scenario has long-term benefits in terms of total (direct) employment in the energy sector in India, mainly from C&I and O&M jobs in solar and wind, it leads to significant near-term losses, primarily in coal manufacturing and coal extraction. In this respect, the NDC scenario presents lesser challenges due to slower declines in coal jobs, especially in the near-term. However, coal mining jobs in this scenario continue their downward trend, leading to lower total jobs in the medium-term. In contrast, total (direct) jobs increase steadily in the 1.5 °C policy.

3.2. Temporal and regional implications of the energy transition—energy jobs

For each of the technologies mentioned in the last section, people are employed all along the value chain—from manufacturing of components (e.g. wafers, cells, modules, inverters, etc for solar PV; nacelle, turbine, towers, and blades for wind power), to C&I of the parts at the project-site, and eventual long-term O&M. Additionally, for technologies involving the combustion of a fuel, jobs are created in fuel supply (biomass production or extraction of fossil fuels). The main points of differentiation

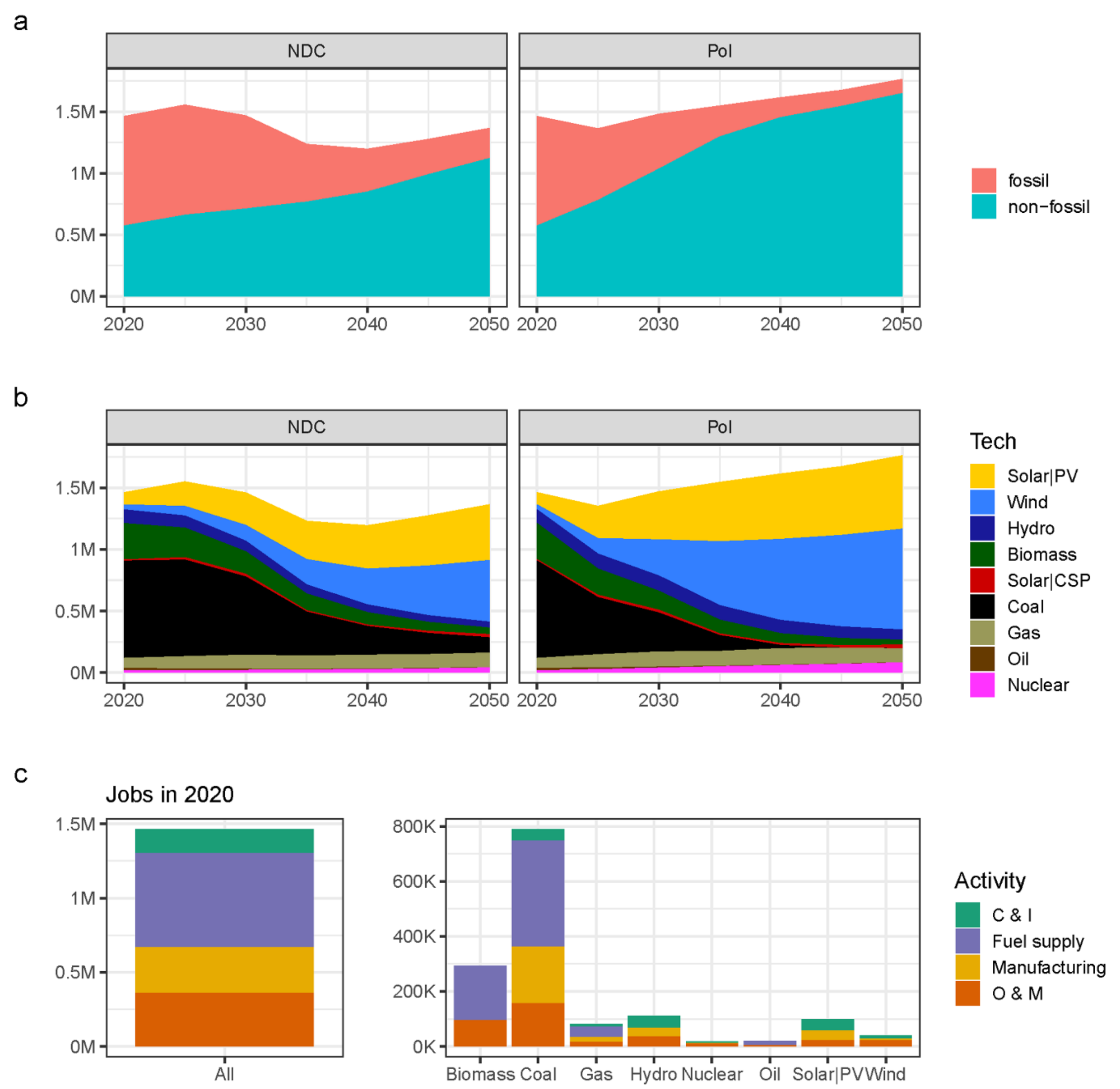

Figure 1. Total energy supply jobs in India by (a) scenario and type (b) by scenario and technology for NDC and 'PoI' (1.5 °C) policy cases, (c) energy jobs in 2020 by activity for different technologies.

between these activities are the location and duration of these jobs. Manufacturing and C&I jobs are essentially short-term and exist as long as there is demand for capacity additions of these technologies. However, unlike C&I jobs, which are often created locally around the project site, manufacturing jobs can in principle be located anywhere. Therefore, the total amount of manufacturing jobs within India not only depends on the energy dynamics in the scenarios but also on the assumption of the share of local manufacturing. On the other hand, O&M and fuel supply jobs are both local, i.e. occur at the location of a power plant and where fuel is available respectively, and are generally more long-term as they are required throughout the lifetime of a specific project.

3.2.1. Solar and wind jobs

The siting of power projects, thus, can have important implications for regional employment. Although the current and near-term spatial distribution of RE is not necessarily a good predictor of future distribution, it is highly plausible that without dedicated interventions, capacity additions in the coming two decades in India, especially until 2030, would occur along existing spatial patterns, i.e. concentrated in the south and west (see figure 3; figure S1 shows the location of under-construction power plants). This is because these regions have higher suitability and superior economics compared to the rest of the country[2] and since absolute resource potentials of solar and wind

[2] The current concentration of solar PV sites can be generally explained by three reasons. First, although solar resource quality (irradiation level) is good across large parts of India (see SI figures S2(a) and (b)), those in the south and west are slightly better (∼10%) than their eastern counterparts. Secondly, sparsely vegetated, and thinly populated areas like wastelands and shrublands with relatively flat topography are considered as the most suitable areas for large solar projects and are predominantly located in the west and (to a smaller extent) south (see figure S2(c)). Both these factors make solar PV projects cheaper in these regions. Lastly, unlike many countries where successful solar rooftop policies led to more spatially distributed installations, these policies failed to gather pace in India. There are many other factors which can affect

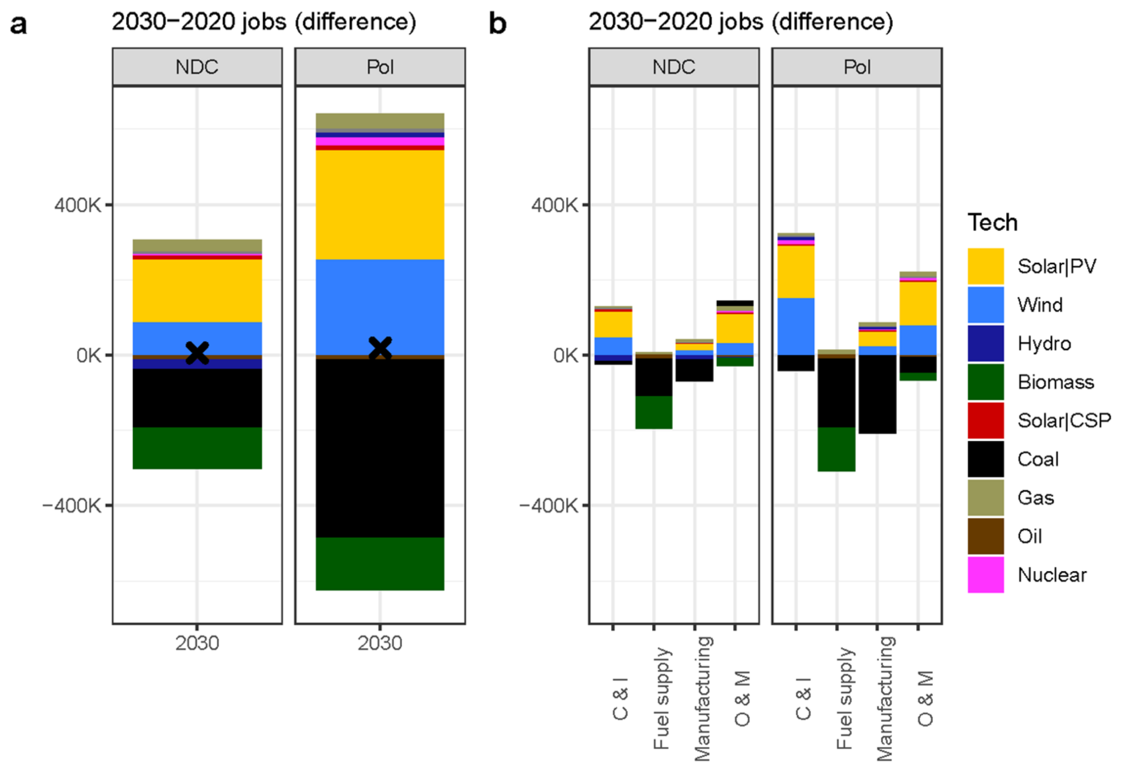

Figure 2. Changes in direct energy jobs from 2020 to 2030 for (a) different technologies (with the black cross denoting the net gain/loss) and (b) technologies and activities, for the two policy scenarios.

energy in these states are big enough to allow for such concentrated deployment. Solar resource potential in these states[3] (light blue bars in figure 3 left panel, totalling ∼24 000 GW) are several orders of magnitudes higher than all-India projected solar capacity in 2040, for both NDC and 1.5 °C scenarios (∼1380 and 2350 GW respectively in 2040; dashed blue and red lines in figure 3—left panel). For Wind, most of the resource potential lies only in the south and west. Additionally, these (solar and wind) capacities would be close to existing industrial demand centres and thus become increasingly economically favourable than standing and new coal power plants[4].

While the siting of power plants affects jobs in C&I and O&M, manufacturing jobs can, in principle, exist anywhere. However, not only does India currently import most of its RE components, especially for solar PV[5], and thus manufacturing jobs exist elsewhere, notably China, but currently operating domestic manufacturing hubs in India are located close to industrial centres in the north, south, and west (see SI table S6). In April 2021 to encourage domestic manufacturing, the government of India announced a production-linked incentive for solar cells, modules, and battery-storage (Carbon Copy 2021a, 2021b). This led to the announcement of several new manufacturing facilities, however, most of them are expected to be located along existing locations (see SI table S6).

3.2.2. Coal jobs

Around half of the current jobs in the coal sector are in fuel extraction (figure 1(c)). These jobs are located close to existing mines, mostly concentrated in four coal-bearing eastern states of Chhattisgarh, Jharkhand, Orissa, and (eastern part of) Madhya Pradesh (red dots, figure 2—right panel). Continuing improvements in labour productivity are leading to declining employment in the sector, e.g. during the period 2015–2020, Coal India Limited (responsible

siting (e.g. favourable policies in certain states, availability of labour or infrastructure, for rooftop—availability of roofs), we consider these effects to be minor.

[3] Represents the sum of Rajasthan (RJ), Gujarat (GJ), Maharashtra (MH), Karnataka (KA), Tamil Nadu (TN), Andhra Pradesh (AP), and Telangana (TG) (see SI table S4 for exact numbers).

[4] Assuming that the capital costs of solar PV, wind, and battery-storage would continue their declining trend, whereas fixed and variable costs of power plants would increase from the installation of pollution abatement technology (Garg 2019), and increase in transport freight costs (Kamboj and Tongia 2018) respectively. While the former would be more uniform across power plants, the transportation costs principally depend on the distance of the power plant and the supplying coal mine.

[5] In 2017–2018, the share of the Indian manufacture in solar cells was 7% of total demand, amounting to 885 MW (Ministry of Commerce and Industry 2018). India does not manufacture polysilicon, wafer, or ingots (Ministry of New and Renewable Energy 2021a). The share of indigenisation of wind components was 70%–80% (Ministry of New and Renewable Energy 2021b).

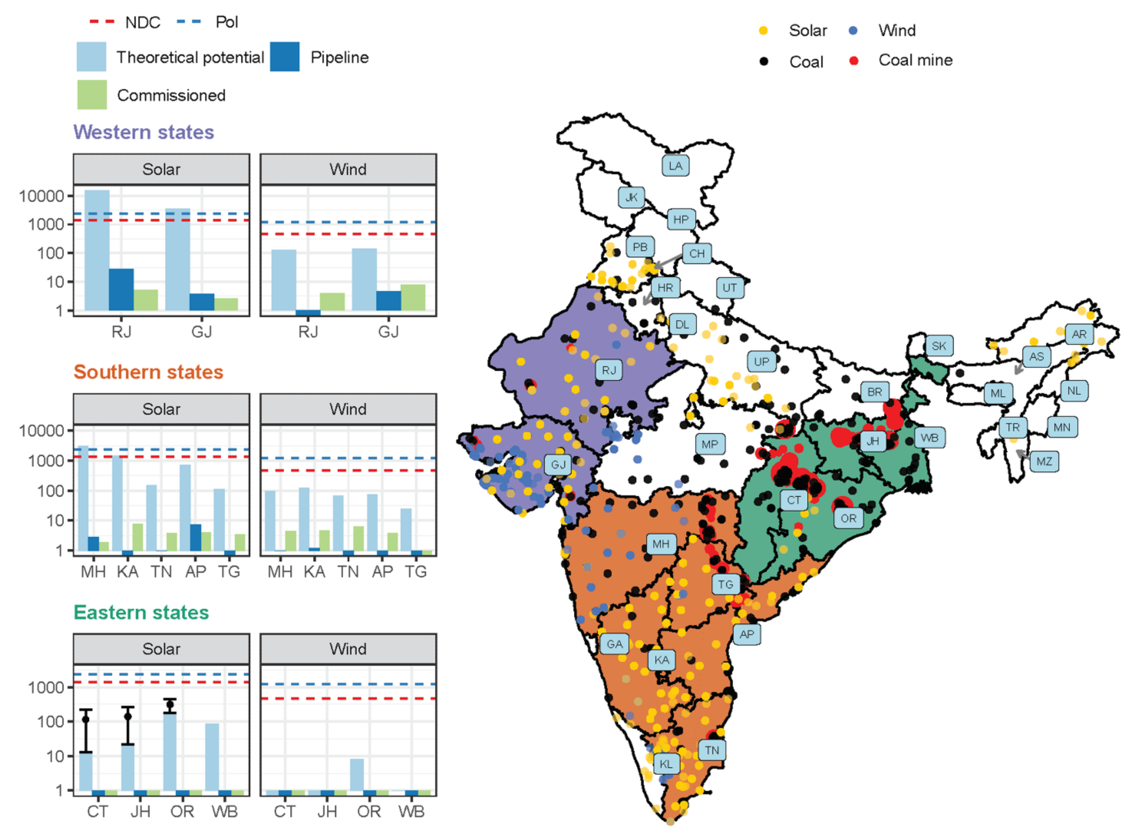

Figure 3. Left panels—solar and wind technical potentials (light blue), using a conservative estimate, commissioned (green) and pipeline (dark blue) power projects (all in GW) for the three 'state classifications': western, southern, and eastern states. For the eastern states of CT, JH, and OR, a range of potentials is additionally represented by black error bars and dots, representing less conservative 'medium' (black dot) and 'high' estimates according to SI table S5. Note the logarithmic scale. The dashed lines, in blue and red, represent all-India solar and wind capacities in the two scenarios: REMIND 1.5 °C ('Pol') and NDC . Right panel—location of currently operating/commissioned coal, solar, and wind installations and coal mines (in red). Size of red sphere proportional to mine capacity. Note that the commissioned/operating capacity for solar and wind on the left and right panel are from different sources. More information, including data sources in the SI section 1.

for almost 80% of total all-India coal production), increased its coal production (in Mt) by 22%, but increases in labour productivity (output per man shift) of ∼25%, resulted in a decrease in the number of people employed (including contract workers) by almost 20%: from 426 000 in 2015 to 342 000 in 2020 (Ministry of Coal 2017, 2020). A continuation of this trend is also visible in the NDC scenario, where despite increasing coal production by ∼50% by 2030, coal jobs decline by ∼20%. In comparison, the strict mitigation in the 1.5 °C scenario leads to an additional loss of 350 000 jobs in the sector.

Bottom-up estimates of jobs in the manufacturing of coal power plant components like boilers, cooling towers, generators, etc are not available but are generally believed to have a larger share of local origin than RE. The model estimates[6] show that in the NDC scenario, these jobs decline by almost ∼29% by 2030, while in the stricter mitigation scenario, all these jobs disappear owing to no new construction of coal power plants.

[6] The employment module assumes that for India, 70% of the manufacture of these components takes place domestically.

Jobs in O&M and C&I are created at or near locations of existing power plants (see figure 2—right panel for locations of operating coal power plants). On the other hand, most of the planned coal capacity until 2030 is concentrated near existing and planned coal mines (see figure S1(d) in the SI for coal plants under-construction and planned coal mines), a few along the coast would probably be dependent on imported fuel.

4. Discussion and limitations

4.1. Regional implications of policies—political economy and inequality

Without additional policies which shape the distribution of energy assets, the projected spatial distribution of power generation assets could have important social and political implications. The increased coal infrastructure in the NDC scenario would occur mostly in coal-bearing states, thereby increasing regional coal lock-ins. Moreover, coal-bearing states are some of the poorest in India and thus an energy transition would redistribute wealth from poor to richer states. Both these factors would create additional political challenges to decarbonisation.

The strength of the opposition to this transition is harder to anticipate; and depends on the power struggle between the state and central government, which jointly legislate energy policy, and societal actors such as private companies, public centre enterprises, and labour unions, which influence policies, e.g. through lobbying. On the one hand, the decreasing share of formal workers in coal mines (Bhushan *et al* 2020) and the overall reduction in labour force (from increasing labour productivity) might lead to weaker pro-coal unions. Moreover, as sectors outside coal continue progressing rapidly[7], the share of coal mining in the state's economic output would decrease, thereby reducing its role in regional economic development. On the other hand, incumbent coal interests in India exist at multiple levels of governance and value chain (Montrone *et al* 2021) and would not diminish in the near-term. Experiences from other countries such as USA and Germany show that regional concentration of fossil jobs, though a relatively small share of overall jobs, can play an important role in electoral outcomes (Oei *et al* 2020).

Without measures aimed at the redistribution of RE assets, coal-bearing states also miss other benefits associated with an increasingly decarbonised economy. These include local environmental benefits associated with reduced coal generation (Rauner *et al* 2020) and coal mining and increasing investments along the RE value chain, leading to higher job creation[8] (though typically lower pay, according to experiences in the U.S., Germany, and South Africa).

4.2. The role of solar energy in a just transition

As mentioned before, just transition is seen as a means to reduce political barriers to an energy transition. Within this theme, one focus has been on employment creation, especially on replacing current fossil energy (regional) jobs with new jobs in clean energy (Kapetaki *et al* 2020, Pai *et al* 2020)[9]. This is because the large investments are anyway required for decarbonisation which might as well go to these regions, and the skill-overlap between coal-related and low-carbon jobs could lessen retraining efforts. At the same time, the extent to which various coal-mining employees would find appeal in low-carbon technologies depend on many factors like substitutability, education and skills levels, salary, and therefore needs to be assessed at a regional level[10].

As previously mentioned, in deep decarbonisation scenarios, coal states would see a drastic drop in coal mining employment and without dedicated policies aimed at redistribution, would receive only a small share of future solar investment/jobs. Investments in wind energy, on the other hand, are constrained by the very low resource potentials in these regions and would thus contribute insignificantly to job creation and ultimately to a just transition.

To estimate how much solar capacity would be needed to replace the losses in the coal mining sector in a 1.5 °C-scenario, we assume, initially a conservative case I, where owing to their long-term nature, only jobs in O&M can replace coal mining jobs and that all installations are utility-scale. From table 2 (see case I), we see that this implies the addition of almost 9 GW yr^{-1} of capacity each year for the next 5 years (until 2025) for each coal state, even doubling thereafter (2025–2030). Given that all-India solar capacity addition for the same 1.5 °C scenario is ∼37 GW yr^{-1} (between 2020 and 2025) and ∼90 GW yr^{-1} (between 2025 and 2030) respectively (figure S3(c)), this implies that ∼70% of the near-term and ∼50% in 2025–2030 of the solar capacity additions need to go to these three states. Furthermore, for Chhattisgarh and Jharkhand, the required total capacity additions in the next 10 years would almost completely exploit their solar technical potentials (under a medium constraint, see SI table S5).

Case II represents a more optimistic assumption where: (a) 20% of the total solar capacity addition takes place as solar rooftop and (b) both jobs in O&M and C&I can replace coal mining jobs.

For both cases, the solar capacity to replace coal mining jobs is a function of the coal jobs to be replaced, the employment factor of the activity, and the activity/activities considered. In case II, the inclusion of C&I jobs and solar rooftop (which has higher employment intensity than solar utility) reduces the required solar capacity (in 2020–2025) compared to case I. However, in the subsequent time step, the decreasing employment factor and the short-term nature of C&I jobs erodes the 'advantage'. The result is that the solar capacity required in the time step (2025–2030) is more similar to case I than in the earlier time step.

Including C&I jobs to replace coal jobs could raise the following qualitative considerations. On the one hand, unlike O&M jobs and coal mining jobs, where people are employed at the same location for a

[7] The share of 'mining and quarrying' in Gross state value added (GSVA), decreased for Jharkhand from 11.65% to 9.6% from 2011–2012 to 2019–2020 (Government of Jharkhand 2020), decreased for Odisha from 12% to 7% between 2011–2012 and 2017–2018 (Government of Odisha 2018).

[8] Solar PV leads to more job creation compared to coal power (including mining), for every GW of capacity or GWh of power production (CEEW 2019)—not including manufacturing.

[9] Kapetaki *et al* (2020) assess the potential of a range of clean energy technologies—bioenergy, solar (rooftop and utility), wind, geothermal, and CCS in coal mining regions of the European Union.

[10] For many core mining jobs (e.g. drillers, miners, shot firers, and semi-skilled machine operators) there are might also be no direct substitutes in renewable energy (Briggs *et al* 2020). Coal workers might have different skills/education levels in different countries, e.g. in Poland and South Africa, they are generally semi-skilled/have basic education (Baran *et al* 2020, Patel 2020).

Table 2. Estimated loss in coal mining employment for the three major coal-bearing states in India, including solar capacity required to replace coal mining jobs for the two cases: (a) Jobs replaced only by O&M in solar utility; (b) jobs replaced by both O&M and C&I and in both solar rooftop and solar utility. For calculations refer to SI section 6.

State	Share of total coal produced (%) (Coal Controller's Organisation 2019)	Estimated loss in coal mining employment during the time period[a]		Case I: only O&M jobs for solar-utility capacity to replace all coal mining jobs (GW)			Case II: total solar capacity to replace all coal mining jobs, assuming the share of solar rooftop to be 20% and considering both O&M and C&I jobs (GW)[b]		
		2020–2025	2025–2030	2020–2025	2025–2030	Total addition	2020–2025	2025–2030	Total addition
Chhattisgarh	22.2	19 000	22 000	47.5	88	135.5	22	56	78
Odisha	19.8	17 000	19 000	42.5	76	118.5	19	49	68
Jharkhand	18.5	16 000	18 000	40	72	112	18	46	64

[a] Assuming state share of coal production remains the same over time.

[b] For calculations refer to SI section 6.

long duration[11], people employed in C&I would need to continuously move to areas of new construction. On the other hand, depending on the education and skills of the people employed in coal mining, C&I jobs might require less retraining effort than O&M jobs. According to Dominish *et al* (2019), almost 46% of the total people employed in coal mining are plant and machine operators and assemblers, constituting the largest occupation share. In comparison, the O&M stage for solar PV employs almost no such occupation, but the C&I stage employs almost 56% of the total people in this occupation, also constituting the largest occupation share for the stage.

In general, assuming only solar jobs to replace the losses from coal mining would involve a significant share of yearly national additions to go to these states.

A potential downside to a dedicated program on capacity additions in these states is that it would imply additional costs. These arise from potentially higher generation costs (around 10%–15%, see SI table S4) due to the relatively lower full-load-hours of solar in the coal states compared to western and southern states. These costs could increase even further if part of the addition comes from solar rooftop (due to higher capital costs of solar rooftop than solar utility). However, these could be financed by the Goods and Services compensation cess or the District Mineral Foundation and Compensatory Afforestation Fund Management and Planning Authority (Prayas and CPR 2020). Either way, these additional costs would be well worth it. Experience from other nations shows that such a transition is often a lengthy process, involving multiple stakeholders and that an earlier transition has the potential to save money and hardship (Oei *et al* 2020).

Lastly, successful decarbonisation would require that all regions develop their RE potentials to some extent, as this benefits the balancing of fluctuations, reduces transmission expansion requirements, and might be needed due to the scale of deployment. Solar installations could benefit from the existing road and transmission infrastructure used to evacuate coal and coal power in coal states and support challenges associated with increasing variable renewable share in the power grid.

In summary, although the role of solar in a just transition depends on many factors listed above, and potentially other compensating mechanisms, its overall role will be limited. But even this could help in gradually breaking existing coal lock-ins and boost medium-term economic diversification and job creation in all regions. These in turn are vital for assuring political support for the energy transition.

[11] Judging from other countries' experiences, coal mines could also serve as sites for PV plants, implying that at least some people in coal mining might not have to move at all.

4.3. Limitations

In this paper we have only explored the role of solar and wind energy in assisting a just transition, however, this (option) should not be considered exhaustive. Bhushan *et al* (2020), e.g. explore other non-energy options like forest-based livelihoods, aquaculture, mine reclamation, etc. Other RE/low-carbon alternatives that have not been considered have either a limited role in India's energy future energy projections (e.g. nuclear and bioenergy) or have limited potential in coal-states (e.g. hydro), or yet to be studied (storage, energy efficiency). Indirect jobs in other energy-intensive sectors would also be impacted by the energy transition—e.g. steel, cement, and transport have also not been considered, mainly due to the limitation of the employment factor approach. Beyond employment creation and retraining, considerations of regional economic development and higher prices for energy consumers could also become critical for a successful transition (Jakob *et al* 2020). In fact, Green and Gambhir (2020), searching through 'transitional planning assistance' literature, provide a useful framework based on groups/agents affected by the transition and various options available to the policymakers, e.g. direct compensation. In this regard, the study has not tried to assess the relative importance of different approaches but concentrated on quantifying the role of energy sector jobs in a just transition. For a complete list of limitations on the employment-factor approach used to estimate energy employment, refer to Malik *et al* (2021).

5. Conclusions

A stringent mitigation scenario leads to higher jobs (direct energy employment) in the long-term in India but leads to significant near-term losses, primarily in coal (power plant) manufacturing and coal extraction. Most of the jobs in the latter are concentrated in a few coal-bearing states. An energy transition will lead to massive investments in solar and wind infrastructure, however, most of this is expected to take place in the western and southern states of India. Eastern coal-bearing states on the other hand will face disinvestment: through the closure of mines and power plants, which will hurt both regional development and local employment. This could create significant political challenges to the energy transition. Dedicated policies to ensure early geographic diversification of solar energy, i.e. significant installations in eastern states could be an important policy component to help build broad support for the energy transition that is required for climate targets and could give India important benefits in terms of avoided climate impacts and additional local health. At the same time, solar alone cannot be the panacea and there is an urgent need for engagement with all stakeholders exploring challenges and opportunities into the transition.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.5901604.

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Conflict of interest

The authors report no conflict of interest.

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