Barriers to power sector decarbonisation in India

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Contents

Abstract

The role of developing countries like India in climate action has undergone a shift in the last five to ten years. Several factors have led to this development. Firstly, with the signing of the Paris Agreement and its emphasis on bottom-pledges, all countries have become co-enactors to mitigation. Secondly, continued scientific research on co-benefits and climate damages has reduced the gap between mitigation and development priorities. Lastly, capital costs of renewable energy (RE) have plummeted making them cheaper than new coal plants in most countries, thereby providing a solid economic incentive to increase the share of RE. Despite these developments, decarbonisation of the power sector in low-income countries faces significant socio-economic and political barriers. This dissertation identifies some of those barriers, eventually suggesting policy solutions to overcome them. While one publication of this cumulative dissertation has a global scope, the other two papers focus on India, a country with low cumulative historic emissions, but is currently the third-largest emitter of greenhouse gases (GHG). Per-capita energy consumption is still low, but it has one of the fastest growing electricity markets in the world. Thus, the policy decisions in the power sector in India can substantially affect the global goal to decarbonisation.

The first publication identifies the risk of carbon lock-ins in the power sector if India were to continue a trajectory based on current policies. We find that continued investment into fossils could eventually lead to stranded assets in the future because of the faster pace of decarbonisation required in scenarios achieving the Paris Agreement goals. Since most of the stranding arises from plants yet to be built, it can be avoided through additional capacity installations of RE, i.e., increasing current ambition in RE-deployment and limiting new coal power plants to those under construction. Most of the additional capacity would come from solar and wind, given their large resource potentials and favourable economic viability in India. The expansion potential of other sources like gas, nuclear, and hydro remains low, owing to constraints on supply, cost , and construction duration.

The second article uses different mitigation scenarios and analyses, on a global level but based on country-specific data, the labor market implications of a decarbonisation policies. Although ambitious policies supporting RE and discouraging coal power, e.g.,

through a coal moratorium, discussed above are favourable for (future) deep decarbonisation, they could lead to disruptive changes adversely affecting the employment situation, specifically the drastic losses in the fossil sector. We show that in the near-term, stringent mitigation results in a net increase in jobs compared to a weaker climate action scenario (based on currently pledged country objectives), mainly through gains in solar and wind jobs in construction, installation, and manufacturing, despite significantly higher losses in coal fuel supply. However, global energy jobs eventually peak, because the falling labour intensity (i.e. jobs per megawatt , due to increasing productivity) outpace increases in RE installations. In the future, total jobs are still higher in stringent mitigation than in a scenario with less mitigation with most people employed in the operation and maintenance of RE infrastructure, unlike fuel extraction today. Although stricter mitigation could lead to higher jobs globally, the role of employment in decarbonisation in specific regions could play out very differently. In countries with significant people employed in fossil-fuel industries, a just transition for those workers could become important.

The third publication highlights that the regional mismatch of energy infrastructure in India could become a significant barrier to effective decarbonisation. Most of the coal mines and coal power plants in India are concentrated in the poorer eastern states of Chhattisgarh, Odisha, and Jharkhand, where it is an important source of both employment and public economy. On the other hand, the best RE potentials in India are concentrated in the relatively wealthier western and southern states and are home to current and planned RE installations. Continued fossil investments in coal-bearing regions could widen this gap and in pathways to deep decarbonisation, strongly accelerate the loss of coal jobs. Without complementary opportunities, this would negatively impact the livelihood of people living in these areas. We show that dedicated policies to increase solar installations in coal regions could ensure early geographic diversification of solar energy. It could help build broad support for the energy transition, required for climate targets, and could give India important benefits in terms of avoided climate impacts and local health. At the same time, solar alone cannot provide a just transition and there is an urgent need for engagement with all stakeholders exploring challenges and other opportunities into the transition.

In summary, despite the proliferation of climate considerations into decision-making at all political levels, there are still significant barriers to decarbonisation. Some of the most pressing challenges for fast-growing economies like India involve avoiding lock-ins in the power sector, which could have far-reaching consequences on the pace and cost of future decarbonisation. Higher-income nations could support the transition by providing cheaper RE-related finance and knowledge of increasing power system flexibility. At the same time, changes in the quantity and structure of jobs in the energy sector could also affect the pace of decarbonisation. Here, one key factor is the just transition of predominantly coal-bearing regions. The regional divide of fossil and RE assets and resources in India means that a regionally balanced transition from a fossil to a RE-based economy would not happen on its own; it needs dedicated policies supporting future solar installations in coal-bearing states. However, given the large size of the current coal workforce, additional solar capacity alone (in these regions) cannot replace all the lost jobs. It therefore requires to look for alternatives beyond the energy sector.

Zusammenfassung

Die Rolle von Entwicklungsländern wie Indien bei den Klimaschutzmaßnahmen hat sich in den letzten fünf bis zehn Jahren gewandelt. Mehrere Faktoren haben zu dieser Entwicklung geführt. Erstens sind mit der Unterzeichnung des Pariser Abkommens und seiner Betonung der "‘bottom-pledges"’ alle Länder zu Mitakteuren beim Klimaschutz geworden. Zweitens hat sich durch wissenschaftliche Forschung über Klimaschäden und positive Nebeneffekte von Klimaschutz die Kluft zwischen Minderungs- und Entwicklungsprioritäten verringert. Drittens sind die Kapitalkosten für erneuerbare Energien (EE) drastisch gesunken, so dass sie in den meisten Ländern billiger sind als neue Kohlekraftwerke, was einen verlässlichen wirtschaftlichen Anreiz zur Erhöhung des Anteils regenerativer Energien bietet. Trotz dieser Entwicklungen sind die sozioökonomischen und politischen Hindernisse für die Dekarbonisierung des Stromsektors in Ländern mit niedrigem Einkommen erheblich. In dieser Dissertation werden einige dieser Hindernisse aufgezeigt und schließlich politische Lösungen zu deren Überwindung vorgeschlagen. Während eine Publikation dieser kumulativen Dissertation eine globale Perspektive einnimmt, konzentrieren sich die anderen beiden Artikel 1 auf Indien, dessen kumulierte historische Emissionen gering sind, das jedoch derzeit der drittgrößte Emittent von Treibhausgasen (THG) ist. Der Pro-Kopf-Energieverbrauch ist immer noch niedrig, aber das Land hat einen der am schnellsten wachsenden Strommärkte der Welt. Daher können die politischen Entscheidungen im indischen Energiesektor das globale Ziel der Dekarbonisierung erheblich beeinflussen.

In der ersten Publikation wird das Risiko von Kohlenstoff-Lock-Ins im Energiesektor aufgezeigt, wenn Indien den auf der aktuellen Politik basierenden Kurs fortsetzen würde. Wir zeigen, dass ein Fortsetzen der Investitionen in fossile Energieträger in der Zukunft zu "‘verlorenem Kapital"’ (stranded assets) führt, sobald die Dekarbonisierung derart beschleunigt wird, dass die Ziele des Pariser Abkommens in den analysierten Szenarien erreicht werden. Da die meisten dieser Fehlinvestitionen aus noch zu bauenden Anlagen stammen, können sie vermieden werden, wenn zusätzliche EE-Kapazitäten aufgebaut und neue Kohlekraftwerke auf die im Bau befindlichen beschränkt werden. Der größte Teil der zusätzlichen Kapazität würde aus Sonnen- und Windenergie stammen, da sie über ein großes Potenzial verfügen und in Indien wirtschaftlich rentabel sind.

Das Ausbaupotenzial anderer Energieträger wie Gas, Kernkraft und Wasserkraft bleibt aufgrund von Einschränkungen bei Angebot, Kosteneffizienz und Bauzeit gering.

Im zweiten Artikel werden verschiedene Minderungsszenarien verwendet und auf globaler Ebene, aber auf der Grundlage länderspezifischer Daten, die Auswirkungen einer Dekarbonisierungspolitik auf den Arbeitsmarkt analysiert. Obwohl ehrgeizige politische Maßnahmen zur Förderung von EE und zur Eindämmung der Kohleverstromung, z.B. durch ein Kohlemoratorium, wie oben erörtert für eine (künftige) tiefgreifende Dekarbonisierung günstig sind, könnten sie zu disruptiven Veränderungen führen, die sich nachteilig auf die Beschäftigungssituation auswirken, insbesondere durch drastische Verluste im fossilen Sektor. Wir zeigen, dass ein strenger Klimaschutz kurzfristig zu einem Nettozuwachs an Arbeitsplätzen im Vergleich zu einem schwächeren Klimaschutzszenario (basierend auf den derzeit zugesagten Länderzielen) führt, vor allem durch einen Zuwachs an Arbeitsplätzen in der Solar- und Windenergiebranche in den Bereichen Bau, Installation und Produktion, trotz deutlich höherer Arbeitsplatzverluste im Kohlesektor. Allerdings erreicht die Zahl der Arbeitsplätze im Energiesektor weltweit letztendlich ihren Höchststand, da die sinkende Arbeitsintensität (d. h. Arbeitsplätze/Megawatt, aufgrund steigender Produktivität) den Anstieg der EE-Installationen überkompensiert. In der Zukunft ist die Gesamtzahl der Arbeitsplätze bei schneller Dekarbonisierung immer noch höher als bei einem Szenario mit geringerem Klimaschutz, wobei die meisten Menschen nicht wie heute in der Brennstoffgewinnung, sondern im Betrieb und in der Wartung der EE-Infrastruktur beschäftigt sind. Obwohl strengerer Klimaschutz weltweit zu mehr Arbeitsplätzen führen könnte, könnten die Auswirkungen der Dekarbonisierung auf die Beschäftigung in einzelnen Regionen sehr unterschiedlich ausfallen. In Ländern, in denen viele Menschen in der Produktion fossiler Brennstoffe beschäftigt sind, könnte die Berücksichtigung sozialer Gerechtigkeit bei diesem Übergang im Sinne einer "‘just transition"’ wichtig werden.

Im dritten Artikel wird hervorgehoben, dass das regionale Ungleichgewicht der Energieinfrastruktur in Indien zu einem erheblichen Hindernis für eine wirksame Dekarbonisierung werden könnte. Die meisten Kohleminen und Kohlekraftwerke in Indien befinden sich in den ärmeren östlichen Bundesstaaten Chhattisgarh, Odisha und Jharkhand, wo sie eine wichtige Stütze des Arbeitsmarkts und der öffentlichen Wirtschaft darstellen. Andererseits konzentrieren sich die besten EE-Potenziale in Indien auf die wohlhabenderen westlichen und südlichen Bundesstaaten, in denen bestehende und geplante EE-Anlagen zu finden sind. Fortgesetzte Investitionen in fossile Energieträger in den Kohleregionen könnten diese Kluft vergrößern und auf dem Weg zu einer tiefgreifenden Dekarbonisierung den Verlust von Arbeitsplätzen in der Kohleindustrie stark beschleunigen. Ohne Alternativmöglichkeiten würde sich dies negativ auf den Lebensunterhalt der in diesen Gebieten lebenden Menschen auswirken. Wir zeigen, dass gezielte

Politikmaßnahmen, um Solaranlagen in Kohleregionen zu installieren, eine frühzeitige geografische Diversifizierung der Solarenergie sicherstellen könnten. Dies könnte dazu beitragen, eine breite Unterstützung für die Energiewende aufzubauen, die für die Erreichung der Klimaziele erforderlich ist, und Indien wichtige Vorteile im Hinblick auf die lokale Gesundheit un die Vermeidung von Klimaschäden bringen. Gleichzeitig kann die Solarenergie allein keinen gerechten Übergang sicherstellen, und es besteht dringender Bedarf, alle Interessengruppen zu beteiligen, um Herausforderungen und weitere Möglichkeiten für diesen Übergang zu identifizieren.

Zusammenfassend gibt immer noch erhebliche Hindernisse für die Dekarbonisierung, obwohl Klimaaspekte bei der Entscheidungsfindung auf allen politischen Ebenen zunehmend berücksichtigt werden. Einige der dringendsten Herausforderungen für schnell wachsende Volkswirtschaften wie Indien bestehen darin, Lock-Ins im Energiesektor zu vermeiden, die weitreichende Folgen für das Tempo und die Kosten der künftigen Dekarbonisierung haben könnten. Länder mit höherem Einkommen könnten den Übergang unterstützen, in dem sie ihre Kenntnisse zur Erhöhung der Flexibilität des Stromsystems anbieten und für eine günstigere Finanzierung erneuerbarer Energien sorgen. Gleichzeitig könnten sich Veränderungen in der Anzahl und Struktur der Arbeitsplätze im Energiesektor auch auf das Tempo der Dekarbonisierung auswirken. Ein Schlüsselfaktor in diesem Zusammenhang ist ein gerechter Übergang in Regionen, in denen überwiegend Kohle gefördert wird. Die regionale Verteilung der fossilen und erneuerbaren Ressourcen in Indien bedeutet, dass ein regional ausgewogener Übergang von einer fossilen zu einer auf erneuerbaren Energien basierenden Wirtschaft nicht von alleine erfolgen würde; es bedarf spezieller politischer Maßnahmen zur Unterstützung des Baus von Solaranlagen in den bisher kohlefördernden Bundesstaaten. In Anbetracht der großen Zahl der derzeit im Kohlebergbau Beschäftigten können zusätzliche Solarkapazitäten allein (in diesen Regionen) jedoch nicht alle verlorenen Arbeitsplätze ersetzen. Daher muss nach Alternativen außerhalb des Energiesektors gesucht werden.

Chapter 1

Introduction

This thesis represents the cumulative work of the last four years investigating the barriers of power sector decarbonisation in developing countries like India. The novel scientific work is presented in three research articles, reproduced here as Chapters 2 to 4. This introductory chapter is divided into five sections: i) provides an overview of key background concepts including the role of developing countries in mitigation action, power sector mitigation pathways, and the role of political economy constraints in decarbonisation, especially the need for just transition; ii) describes the conceptual framework used as a guiding principal in our investigation , iii) outlines the research objectives; iv) introduces various methodological tools used in the thesis, including a comparison with other methodologies; v) presents the structure of the thesis.

1.1 Background

1.1.1 Mitigation policies in developing countries

The period between the Conference of Parties (COP) 17 in Durban (2011) to COP 21 in Paris (2015) marked a shift in the regime of climate negotiations and climate action (Sengupta, 2019). Up until Durban, the core responsibility of climate mitigation rested squarely on the shoulders of the rich or high-income nations (Annex-I countries), as enacted in the Kyoto Protocol. Based on the principles of 'equity and common but differentiated responsibilities and respective capabilities' (Article 3.1 of the United Nations Framework Convention on Climate Change UNFCCC (1992)), it was paramount that they 'walk-the-talk' and take a lead in strong mitigation measures. Low-income nations (non-Annex I), who had historically low responsibility (see Figure 1), and low per-capita energy consumption would instead continue to focus on their right and pursuit to economic and social development, i.e, poverty eradication and building essential infrastructure and services for their population. Although it was already clear in the run up to Durban that developed countries, particularly the US, wanted greater commitments and accountability from developing nations, it was not until COP 19 in Warsaw (2013) that the regime shifted, according to Sengupta (2019), from an earlier " 'top-down', 'strictly differentiated', 'legally binding', 'targets and timetables-based' approach towards 'more voluntary', 'less differentiated', 'bottom-up', 'pledge and review'-type system". In Warsaw, all parties to the UNFCCC were invited to voluntarily prepare and communicate their 'bottom-up' national-level pledges on climate action or Intended Nationally Determined Contribution (INDC) until the COP 21 in Paris. These would come into force after the end of the second period of the Kyoto protocol in 2020.

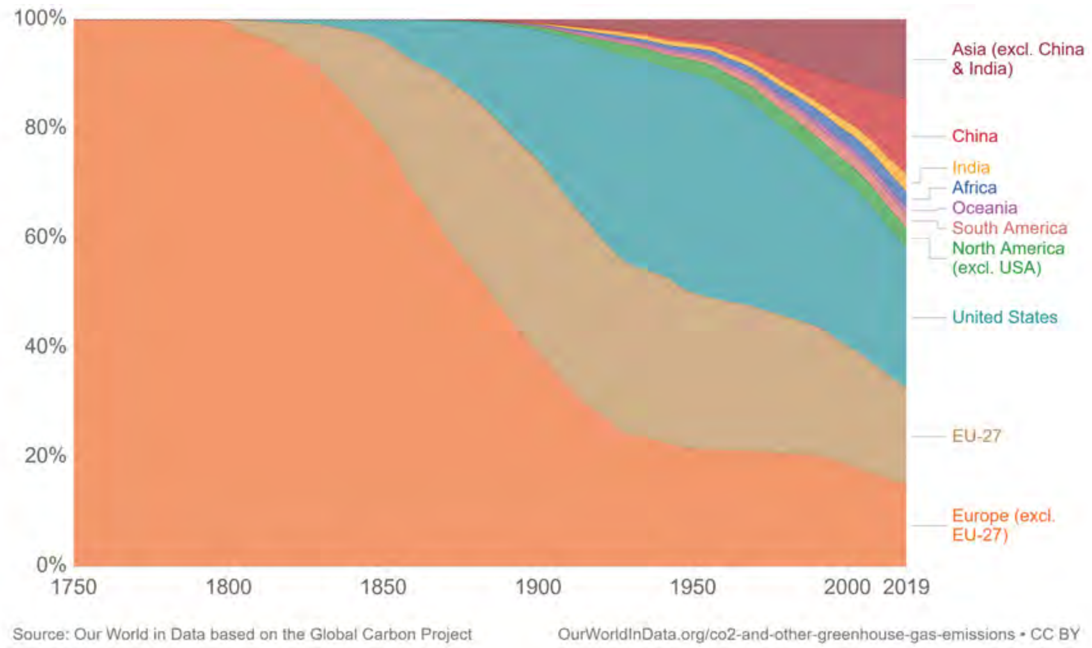

Figure 1: Cumulative carbon dioxide (CO_2) emissions by region from the year 1750 onwards. Emissions are production-based (do not account for emissions embedded in trade). Includes CO2 emissions from fossil fuels and cement production only. Land use change is not included.

This shift was eventually visible in the INDCs (later NDCs) — where around 120 countries had some sort of emissions targets, around 50 countries had some type of share targets (e.g., the share of renewable in primary energy), and 15 countries had capacity targets; although many (higher or stricter) targets were conditional to international financing (Rogelj et al., 2017). India and China, both significant to the future course of emissions, also announced an emission intensity and peaking year target respectively, marking a significant departure from their previous positions.

Fast forward to 2019 and nearly all countries in the world had renewable energy support policies, although with various levels of ambition and scope; 166 countries had renewable power targets, and there were at least 56 carbon pricing initiatives in 47 countries (see Figure 2). As mentioned before, a part of this change came from international

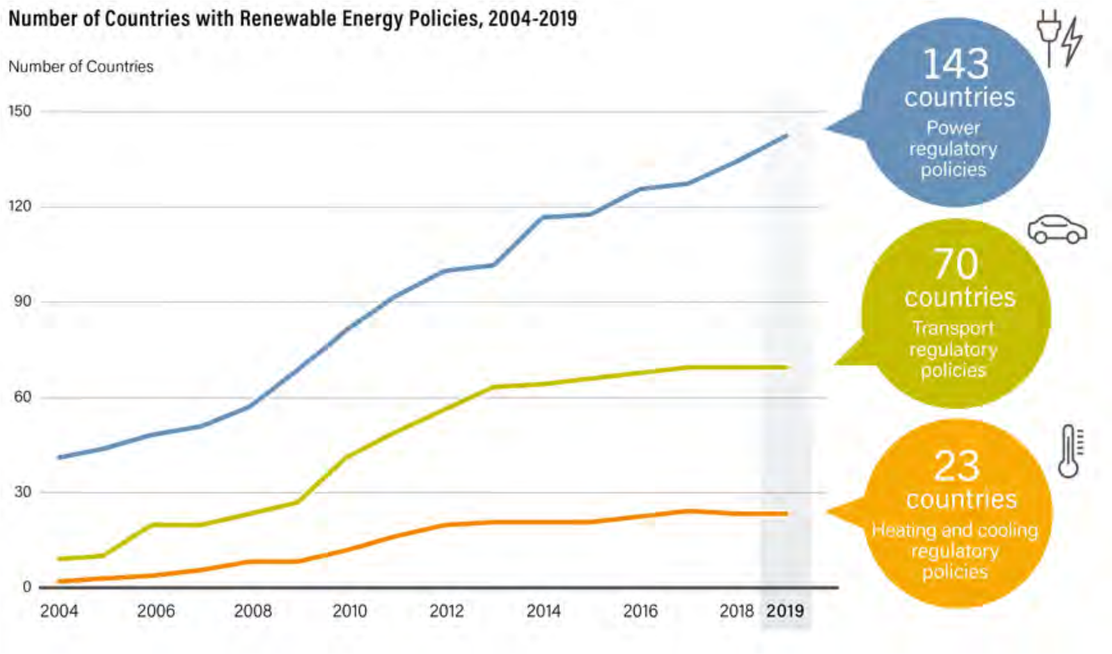

Figure 2: Figure showing the number of countries with renewable energy policies from between 2004 to 2019. Power policies include feed-in tariffs (FITs), feed-in premiums, tendering, net metering and renewable portfolio standards. Transport policies include biodiesel obligations/mandates, ethanol obligations/mandates and non-blend mandates. Heating and cooling policies include solar heat obligations, technology-neutral renewable heat obligations and renewable heat FITs. Figure and caption from Global Status Report, REN21 2020.

pressure, especially through climate negotiations. However, several other factors have provided further impetus to decarbonisation:

1. Driven by a drastic drop in prices of photovoltaic modules and wind turbines and RE support policies, new RE-based power generation became more cost-effective than new coal-fired plants in nearly all countries (REN21 Secretariat, 2020). In India and China, it became even cheaper to build new RE than operate some existing coal power plants (Runyon, 2021).

2. There was an increasing understanding that many of the objectives of developing countries (e.g., energy access, energy security, improving human health) could also be achieved (or at least be complemented) through enhanced climate action (co-benefits) (Dubash, 2013): many developing countries have abundant solar/wind energy but limited or no fossil fuels, therefore RE could provide energy security and even reduce fossil fuel import bills over the long-term (IEA, 2021); energy access in rural areas could be better achieved through decentralised RE than fossil-fuel-based systems (Arent et al., 2017); air pollution benefits from a coal phase-out alone could be sufficient to warrant action, even without considering climate impacts (Rauner et al., 2020).

3. Lastly, through continued research on climate impacts, including the observed

> increase in impacts in most parts of the world (Williams et al., 2019), it became increasingly clear that climate impacts could significantly push back development gains (Dubash, 2019), with developing countries being much more vulnerable and thus, mitigation at home and strong climate action internationally were important for national interest (Thaker and Leiserowitz, 2014).

Armed with strong reasons to decarbonise, the starting point for most low-income countries was the power sector, as also illustrated in Figure 2, which shows the increasing adoption of power regulatory policies. Moreover, a decarbonised power sector was also an essential foundation for future decarbonisation of other sectors, e.g., transport and heating. The next section describes the pathways to power sector decarbonisation along with its various challenges.

1.1.2 Power sector decarbonisation

The power sector, alternatively called the electric power sector, "consists of electricity only and combined heat and power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public" (EIA, 2021). In the year 2018, the sector contributed to ~30 % of all greenhouse gases (GHGs) emitted in the world (Climate Watch, 2021). In the last ten years, emissions from the sector have increased by ~10 %. The decreases in emissions from the EU and the US (mainly through the switch from coal to cheaper gas) more than offset by increasing coal-powered generation in China and India (see Figure 3).

There are indications that emissions in the sector could have already peaked in 2018, especially if the growth of low-carbon energy outpaces future demand growth (Bertram et al., 2021; Lolla, 2021). As mentioned before, RE (especially solar energy) is now cheaper than new coal power in both China and India, where a significant share of future demand is estimated.

1.1.3 Political economy of decarbonisation and the role of just transition

Mitigation pathways have traditionally been relied on techno-economics, focusing on including a wide array of technologies which can be used to decarbonise the different sectors :electricity generation, industry, transportation, and buildings. In the process they have answered questions on 'how much to invest, in what, and by what time?'. However, as power-sector decarbonisation became increasingly mainstream and essential in policy-making, real-world discussions have also become more political and nuanced,

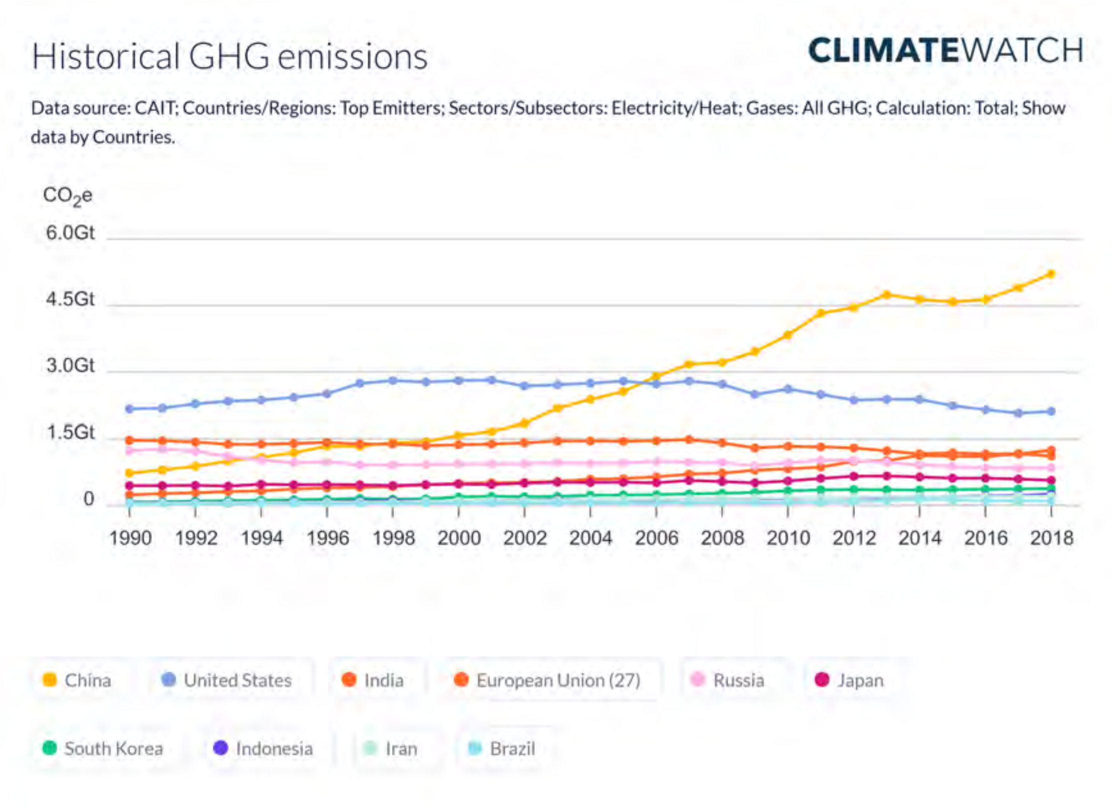

Figure 3: Historical emissions from the power sector, in Gigatonne (Gt) CO2 equivalent, from 1990 to 2018. Figure from climatewatchdata.org

with a focus on the near-term. In turn, this has led to calls to include dimensions of (political) feasibility in mitigation pathways (Anderson and Jewell, 2019) and explore near-term policies which can effectively reduce emissions and provide development gains and/or pass through political or economic hurdles.

Several studies have eventually explored these connections. Pahle et al. (2018); Meckling et al. (2015); Green and Denniss (2018), e.g., argue that although policies favouring low-carbon such as feed-in tariffs [1], R & D subsidies, etc. (also called supportive supply-side policies) or fossil fuel ban/moratorium etc. (also called restrictive supply-side policies) are considered suboptimal as policy options (compared to carbon-pricing), they have numerous economic and political advantages - e.g., they can create (counter) constituencies to fossil fuels in the renewable energy industry and produce their lobbying efforts. Rauner et al. (2020); West et al. (2013) show that linking air pollution to mitigation also has immense potential to achieve wide agreement and ease feasibility. Iyer et al. (2015) show that the high upfront capital costs associated with solar and wind generation, and the higher perceived risk of investment in developing countries (leading to higher financing costs), implies that financial constraints could prevent low-carbon

[1] "A feed-in tariff is a policy tool designed to promote investment in renewable energy sources. This usually means promising small-scale producers of the energy such as solar or wind energy an above-market price for what they deliver to the grid" (Will Kenton, 2021)

investment in these countries, possibly locking them into carbon technologies. Lastly, McCauley and Heffron (2018); Healy and Barry (2017) argue that the energy transition will fail to gather pace unless losers of the transition (be it businesses, states, or unions), especially those who are poor or spend significant income on acquiring energy, are not adequately compensated (e.g., through recycling of carbon tax revenue) or not involved in the decision-making process. These will be elaborated on in the subsequent sections.

The idea behind *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. To a lesser extent, it also implies that the benefits from a transition, in the form of additional jobs created in the supply chain, better air (through cleaner power plants), or cheaper power are not concentrated in certain regions. The worst instance would be e.g., that affected regions and people are not compensated in any way and renewable-related infrastructure is constructed and developed in far-off regions, ultimately forcing the people to emigrate to look for a better life or if they are too old to acquire new skills or jobs, remain unemployed.

The concept of just transition first emerged from trade unions in the 1970s in the US against the loss of jobs from environmental policies (Morena et al., 2018). They acknowledged that although some industries were leading to local environmental and health problems, simply shutting them down was not a reasonable solution, and instead, public policies should focus on addressing environmental problems, simultaneously securing decent jobs and livelihood for the affected workers (Morena et al., 2018). The just transition movement gained widespread agreement and popularity in the US, but it was only in the early 2000s, through other trade unions in the Global North and supported by powerful groups like the International Trade Union Confederation (ITUC), that its ideas diffused into mainstream climate negotiations (Morena et al., 2018). The term was repeatedly used in various COPs, eventually leading to the adoption of the *Solidarity and Just Transition Silesia Declaration* in COP 24 in Katowice, Poland (2018) by 52 countries, with the aim of main-streaming its message in global climate policy (COP 24, 2018). In the last few years, several countries, especially those belonging to the Powering Past Coal Alliance (PPCA) have put forward proposals or policies to promote just transition[2].

A number of recent studies have tried to quantify the elements of a just transition, although often limiting their scope to 'workers in coal-regions' and seeking their alternative re-employment or retraining opportunities in low-carbon industries. Kapetaki

[2]Examples include the 'Task Force on Just Transition for Canadian Coal Power Workers and Communities in Canada' (Canada, 2018), in the EU through the 17.5 billion €'Just Transition Fund' (Commission, 2020), in Germany through the 'Coal Commission - A Roadmap for a Just Transition from Coal to Renewables' (Litz et al., 2019).

et al. (2020), focusing on the EU, identify the jobs and regions, set to lose most from a decline in coal mining and provide estimates of how clean energy deployment, including energy-efficiency measures could (positively) impact job creation and regional economic development. For the latter, they also look at what industries in the value-chain (e.g., nacelle manufacture for wind turbines, RE developers, battery production) already exist and thus be more conducive to particular transition solutions. Pai et al. (2020) look at the locations of coal mines in four countries (United States, China, India, and Australia) and analyse if areas around these regions are conducive to solar and wind installations. They then estimate how much RE capacity would need to be installed to re-employ everyone in the coal mining sector. They focus only on O & M jobs in RE, due to their long-term job security, similar to coal mining jobs. Briggs et al. (2020), focusing on Australia, look at the transition from a more occupational viewpoint, i.e., which jobs in the coal sector overlap with RE jobs, and what people could be retrained easily to the latter. Dominish et al. (2019) compare (globally) types of occupations in the energy sector across in different mitigation scenarios and find that "jobs created in wind and solar PV alone are enough to replace the jobs lost in the fossil fuel industry across all occupation types". Lastly, Bhushan et al. (2020) attempt to ascertain the dependence of coal mining on the communities living around it [3] and use the knowledge to create a just transition framework for India. Unlike other studies focusing particularly on renewable energy, they look into greater depth at alternate livelihood opportunities and economic diversification; although only qualitatively.

1.2 Conceptual framework — barriers to power sector decarbonisation

The barriers to power sector decarbonisation can be broadly grouped into three categories: *techno-economics*, *governance and institutions*, and *socio-economic and political barriers* (Figure 4). The framing of these barriers is similar to that of carbon lock-ins first elicited by Unruh (2000) (also used to understand barriers to mitigation) and eventually adapted and expanded by Seto et al. (2016). However, the present classification is purposely broader to include elements not fully considered in the carbon lock-in approach, e.g., energy justice and financial considerations (access to capital). The classification is useful to understand that each classifier has actors who try to fulfil their own interests (or have their limitations) and systems that have their characteristics — e.g., the election cycle, the long lifespan of carbon infrastructure, etc. The three classifiers are briefly discussed below:

[3] they do this for the district of Ramgarh using primary surveys.

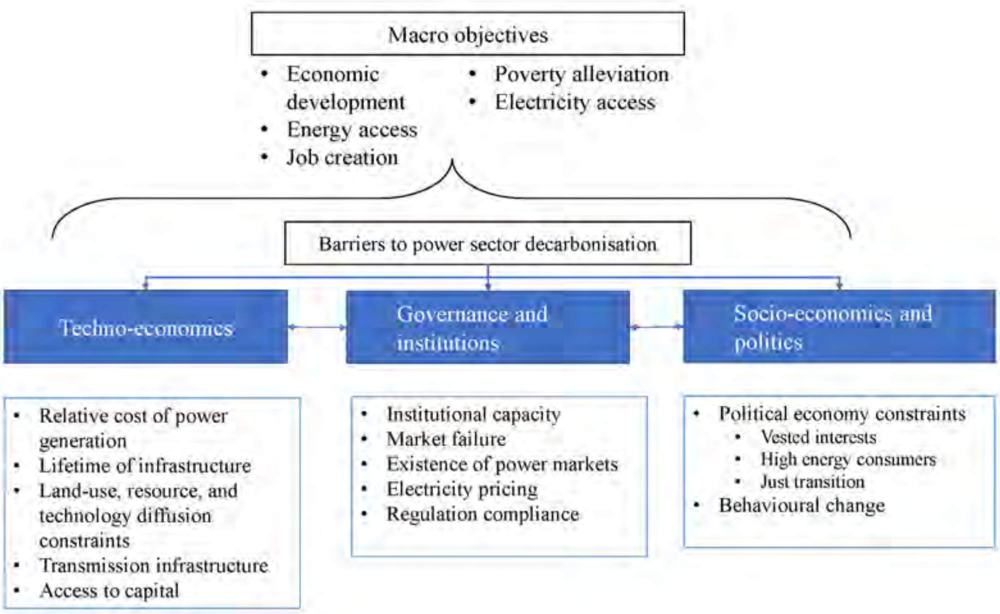

Figure 4: Conceptual framework of the thesis classifying the barriers to power sector decarbonisation

1. **Techno-economics**. The techno-economic barriers refer to the relative costs of different power generation technologies, specifically the costs associated with developing a low-carbon power infrastructure compared to a more passive fossil-based power system. Additional constraints like land can become important in regions of high population density or limited suitable sites. Moreover, high up-front capital requirements (difficulty in accessing finance) can prevent the growth of solar and wind, even if it is competitive to fossils. Lastly, the long lifetime of power infrastructure creates path-dependency preventing optimal outcomes in the future (carbon lock-ins).

2. **Governance and institutions** refer to how the power system is governed including the structure of its institutions along the whole life-cycle — starting from generation to transmission-and-distribution (T & D) and eventually consumption. Barriers here include the short time horizons of politicians which make them risk-averse to potentially disruptive technologies or in other words, continue following the status quo. They could also be in form of limited institutional capacity, e.g., although climate action and sustainable development cut across traditional sectors, work between them may not be aligned; it could also mean limited know-how on how to connect traditional objectives with mitigation objectives (Dubash, 2019).

3. **Socio-economic and politics** concerns mainly with political economy constraints and behavioural change. The former refers to consumers, citizens, and corporations who will be negatively affected by an increase in costs of fossil fuels and will therefore try to oppose change or lobby for weaker change (Jenkins, 2014). On

the other spectrum, it might impact the access to food and energy of the world's poor (Fujimori et al., 2019). At a larger scale, decarbonisation has been opposed by nations and nation-states which receive significant revenue through fossil fuels. Decarbonisation policies must therefore address these constraints through additional policy measures. Behavioural change refers to the (individual) patterns and habits of food, mobility, and housing requirement expressed partially through metrics like ecological footprint and carbon footprint. Constraints resulting from resistance to changing habits are less important in power sector decarbonisation and more relevant for land-use emissions (van de Ven et al., 2018).

1.3 Research objectives

For the major part, this thesis **focuses on the barriers to power sector decarbonisation in India**. This is because: Firstly, although India is currently the world's third-largest emitter, it's share of historic emissions has been low and its per capita electricity and energy consumption are still well-below the world average. Millions of people still don't have access to reliable electricity and clean energy. Secondly and consequently, this means that 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 it meets its future energy demand, particularly electricity, has important implications for itself and the rest of the world. Lastly, India has one of the largest reserves of coal and is currently the second largest coal consumer in the world after China. Coal and coal-based electricity plays an important role in national and regional politics. Thus, any alternatives to coal need to have strong economic arguments and need to be able to deliver increasing power generation both cheaply and reliably.

The research objectives of the thesis were identified based on the underlying conceptual approach described in Section 1.2 and assessing the gaps in existing literature. These gaps could be thematic e.g., focusing on political factors that influence the pace of decarbonisation instead of the usual techno-economics but also methodological, e.g., comparing results between different types of models. This approach led us to three principal objectives, enumerated below:

1. How could near-term policies in India impact longer term decarbonisation efforts required to achieve Paris Agreement targets? What set of decarbonisation options does India have in the near- and long-term?

2. How do different decarbonisation scenarios change the number and structure of jobs globally and within major countries in the energy sector and what impact

	Spatial focus	Temporal focus	Methodological tools used	Key concepts and indicators
Ch. 2	India	2030 and 2050	IAMs, national energy models, model intercomparison, bottom-up data on policies and planned capacities, scenario development	IAMs (Section 1.4.1), model intercomparison (Sections 1.4.2 and 1.4.3), stranded assets and committed emissions (Section 1.4.4)
Ch. 3	Global and large regions	2030 and 2050	Employment-factor approach, IAMs, scenario development	Estimating energy employment, including employment-factor approach (Section 1.4.5)
Ch. 4	sub-regions in India	2030	Employment-factor approach; IAMs; scenario development; bottom-up data on operating, under-construction, and planned energy infrastructure; just transition	See cell above and discussion in Section 1.1.3

Table 1.1: Key methodological tools, concepts, and indicators employed in the thesis

does it have on the success of decarbonisation policies?

3. How do current energy policies and strengthening of RE targets in India and its different states impact the distribution of energy assets and energy jobs across the country and how could it affect the pace of decarbonisation viz. the concept of just transition?

1.4 Methodology

The objectives in Section 1.3 are investigated using different methodological tools which are summarised in Table 1.1. Special focus is given on the near-term and on bridging model results with bottom-up developments in the energy sector. The key concepts and indicators of each study are also mentioned in Table 1.1 and explained in detail in the subsequent subsections.

1.4.1 Integrated Assessment Models

Integrated Assessment Models (IAMs) are numeric models representing features and interactions of natural and human systems, thereby combining knowledge spread across various disciplines (Weyant et al., 1995; Rogelj et al., 2018). The integration allows understanding and insights not usually available through disciplinary research. The main objective of IAMs is to inform policy and decision-making e.g., by analysing policy impacts towards a given goal, analysing benefits and trade-offs of policies across different sectors, and setting research priorities (Weyant, 2017). According to (Wilson et al., 2021), these models

1. represent explicitly the drivers and processes of change in global energy and landuse systems linked to the broader economy, often with a high degree of technological resolution in the energy supply.
2. capture both biophysical and socio-economic processes including human preferences, but do not generally include future impacts or damages of climate change on these processes
3. project cost-effective 'optimal' mitigation pathways under what-if assumptions or subject to pre-defined outcomes such as limiting global warming to 2 °C (Sathaye and Shukla, 2013)

Differences in process-based models

In general, IAMs are grouped into broad categories. The first, called benefit-cost models includes the more stylised IAMs like DICE, RICE, FUND, etc. which have simplified representations of energy and land-use systems and are, as the name suggests, often used for cost-benefit analyses. The second class, called process-based or detailed-process models, include a detailed representation of regions, sectors, and technologies and can thus a provide wide variety of scenarios (Weyant, 2017). This thesis exclusively focuses on the latter.

Process-based models further differ from each other on numerous aspects, some of which are captured by Krey (2014) and grouped into three categories: 1) **system boundaries**, (2) **heterogeneity or level of detail**, and (3) **mathematical solution concepts**. These differences are relevant when examining if the model(s) are equipped to answer specific research questions and to what extent. While some of these limitations can be addressed through model inter-comparison (see Section 1.4.2), caveats and limitations of any modelling study should be made explicit. The differences between these models are explained below and illustrated in Figure 5.

1. **System boundaries** refers to the level of integration among natural or socioeconomic sectors (e.g., electricity sector, whole energy sector, biosphere and climate system), time-horizon, and regional (dis)aggregation. A larger integration within various systems or sectors generally leads to lesser detail within the components, mainly because of computational or institutional limitations. It is important to note that higher resolution/detail doesn't necessarily translate into 'better'

results, because it might introduce additional uncertainties, especially when projecting far into the future.

2. Closely linked to the last point is the **heterogeneity or detail of the model**. This includes spatial heterogeneity, i.e., regional (dis)aggregation (representation of different countries and sub-regions (states)), sectoral/technology representation (e.g., types and categories of power-plants; endogenous or exogenous learning which influences their costs and performance), socio-economic representation (e.g., urban vs. rural classification, income heterogeneity, education levels).

3. The last category of differentiation, called **solution concepts** rests on whether: i) models optimise or simulate, ii) how they treat time (myopia/foresight), and iii) type of equilibrium concept used.

   Optimization models attempt to find an optimum minimum or maximum of a numerical problem. These are generally the "utility of representative agent, consumer and producer surplus, or total energy system costs" (Krey, 2014). On the other hand, simulation models do not optimise anything but based on the relation between variables and some initial condition, simulate the state of these variables.

   The treatment of time can be an important representation of how 'real' world decision-making is performed and can be further divided into a) Static models, b) Recursive-dynamic models , and c) models with inter-temporal (perfect-foresight). Static models simulate or optimize the state of a system at a certain point in time, typically dependent on some initial conditions like an existing energy infrastructure that cannot be changed.

   Recursive dynamic models simulate/optimize the state of a system sequentially, one period at a time, and then pass on the result of this time step to the following time step which uses them as initial conditions. In contrast, inter-temporal energy models compute the results for all periods simultaneously; the computation being usually the optimization of criterion "such as the cumulative discounted utility of a representative agent or cumulative discounted system costs" (Krey, 2014). Lastly, two main equilibrium concepts are used — either partial equilibrium models (e.g., energy system models) or general equilibrium (e.g., CGE or endogenous growth models). "Partial equilibrium models only represent a subset of economic sectors (e.g., energy and/or agricultural sectors) and take certain boundary conditions as a given (mostly the demand for energy or energy services), general equilibrium models represent all economic sectors in a stylised way and thus include a feedback on the demand for energy services and other goods." (Krey, 2014)

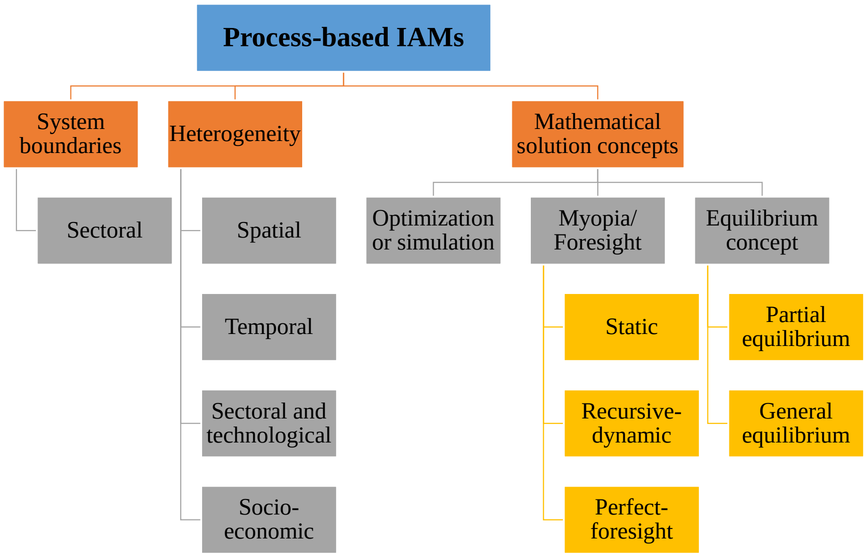

Figure 5: Diagram illustrating important points of difference between process-based IAMs. Own illustration based on classification by Krey (2014).

1.4.2 Multimodel intercomparison studies

Since models differ on a variety of aspects and integrate a complex suite of disciplines characterised by deep uncertainties, model evaluation becomes critical (Wilson et al., 2021; Krey, 2014). The aim of model evaluation is to assess the performance of the model in terms of how good they are for their intended use (Oreskes, 1998). This in turn helps to improve their usefulness and robustness for policy analysis. One of the methods for model evaluation involves model inter-comparison projects (MIPs). These compare outputs and insights across a range of models by designing scenarios that harmonise key assumptions or drivers. These could be socio-economic developments (Riahi et al., 2017), policy assumptions (Tavoni et al., 2015), carbon budgets (Bertram et al., 2021), technology assumptions (Bosetti et al., 2015), etc. The final aim is to generate robust insights that are to a large degree independent of modelling approaches and parametric assumptions (Krey, 2014).

1.4.3 Global and National model intercomparison

Most of the studies mentioned in the preceding section consider only global models of integrated assessment. They include inter-regional trade, the pace and cost dynamics of new technologies, and the link between the global economy with the global climate system. Most of them are technology-rich, giving the energy system a variety of decarbonisation options. On the other hand, national models, which often only include the energy sector, generally consider national circumstances and constraints in more detail. A comparison of the two can thus lead to interesting insights in plausible country decarbonisation pathways.

1.4.4 Committed emissions and stranded assets

Energy infrastructure, particularly power plants, have long lifespans making them prone to path-dependence, thereby locking the system into a carbon-based trajectory [4] and preventing alternatives to emerge. A number of studies have identified the risk of carbon lock-ins through near-term investment in fossil-fuel related infrastructure (see e.g., Bertram et al., 2015; Erickson et al., 2015; Johnson et al., 2015). Such lock-ins can occur for both developed nations, who plan to reduce their carbon intensity by investing in gas-based power, coal plants with higher efficiency, coal with CCS etc. and for developing nations, who wish to quickly expand power generation through build-up of (unabated) coal power. These can eventually bind nations to suboptimal power systems by preventing the entry of cheaper renewable energy and lead to stranding in the face of stringent mitigation policies.

Two key interlinked metrics have been used to illustrate how this ‘infrastructure-inertia’ (Davis et al., 2010) affects mitigation, namely i) **committed emissions** and ii) **stranded assets**. Committed emissions refers to emissions resulting from continued (historical) use of CO2-emitting infrastructure. This infrastructure could either be already standing, under-construction, or planned. To convey the connection to mitigation action, Tong et al. (2019) show that the committed fossil-fuel emissions from existing infrastructure would alone exceed the 1.5 °C carbon budget or consume two-thirds of the 2 °C carbon budget. Moreover, over 50 % of these emissions arise from power-plants. These shares climb even further when proposed power plants are taken into account. However, committed emissions is not a static concept: economy and policy-constraints greatly influence the lifetime and operation of energy infrastructure and from therein emerges the second metric of ‘stranded assets’. Defined broadly, a stranded asset refers to any piece of equipment that is used below its ‘expected operation and lifetime’. For a power plant, this is the unused capacity when a plant is operating below its designed load factor (Johnson et al., 2015). This has the effect of reducing revenues for the generator and/or delaying the time when the generator accrues ‘enough’ profits for the investment to be justified. In the worst case, the operating losses can force the plant to retire early. Stranded assets in the context of climate policy thus provide a measure of investment risk of existing and planned energy infrastructure as well as an indicator of resistance to be faced against stringent climate action.

[4] assuming infrastructure is based on fossil fuels.

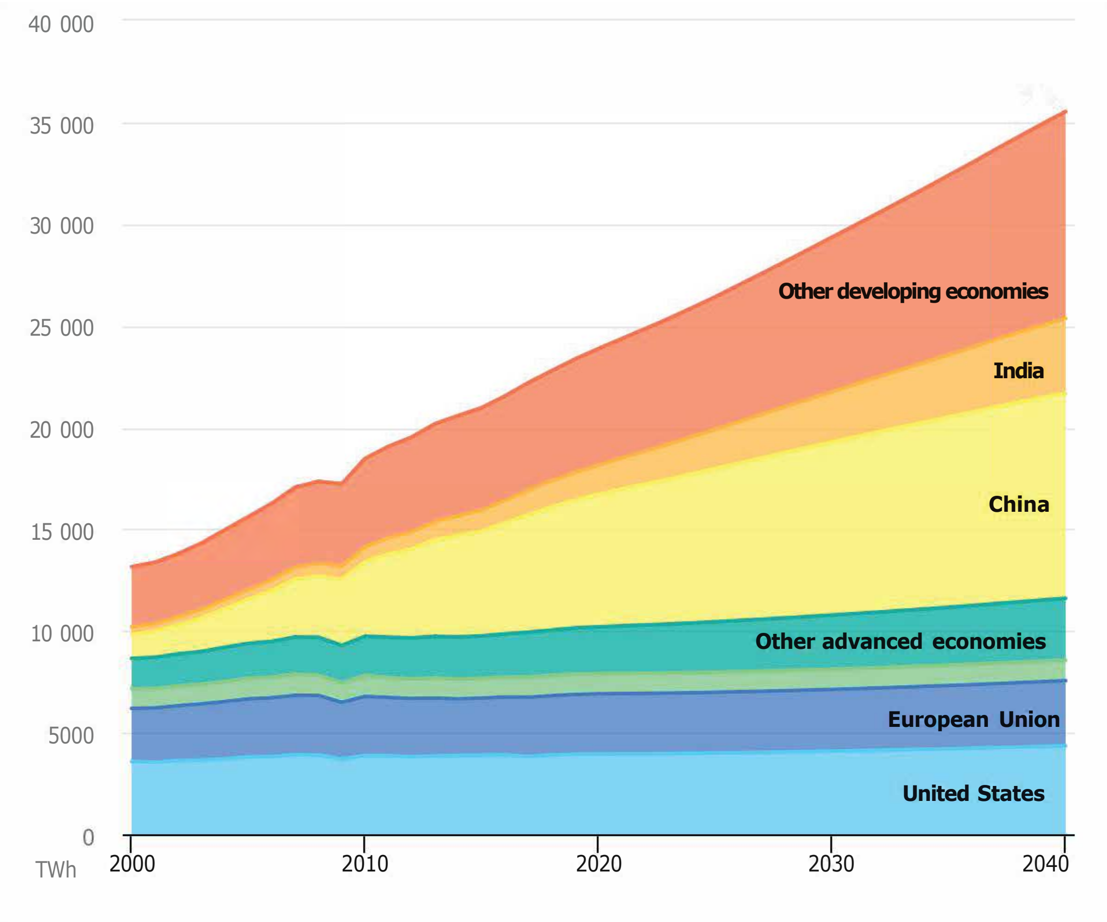

Figure 6: Global electricity demand by region in the New Policies Scenario (IEA), 2000-2040 (IEA, 2019)

1.4.5 Employment assessment of energy policies

Methods of employment assessment can generally be divided into two main approaches, i) ex-post (bottom-up) analytic approach using employment factors, and ii) the use of (top-down) Input-Output (IO) or CGE models where employment is an internal modelled variable (Kammen et al., 2004; Breitschopf et al., 2012). The employment factor [5] approach uses as labour market indicators the ratio of Full-time-equivalent jobs (FTE, sometimes called Jobs-year equivalent) to MW capacity (or MWh/year or dollars invested). These values are disaggregated into stages or activities of production (e.g., Manufacturing, Construction and Installation, etc.)[6]. These activities are then combined (depending on the activity) to actual and installed capacity, to get jobs by activity and sector (wind, solar). In comparison, IO and CGE models include the flow of goods and services between the sectors of the economy; i.e., everything produced either serves as an input to the next level of production or has an end-use purpose (IRENA, 2014). This knowledge of inter-linkages between the economic sectors allows finding the macro-economic impacts (gross or net employment change), including employment, of various energy and climate policies (Lambert and Silva, 2012). Secondly, unlike the employment factor approach, where most studies restrict themselves to assessment of direct employment (in one sector), the I/O approach can often inform about indirect or induced effects (spanning other economic sectors). A summary of the two approaches including their advantages and limitations is shown in Table 1.2.

[5] In some studies also called as labour intensity (Simas and Pacca, 2014; Lambert and Silva, 2012).

[6] Simas and Pacca (2014) even further disaggregate the activities, e.g., manufacturing into manufacture of components of a wind turbine - nacelle, rotor, blades, tower.

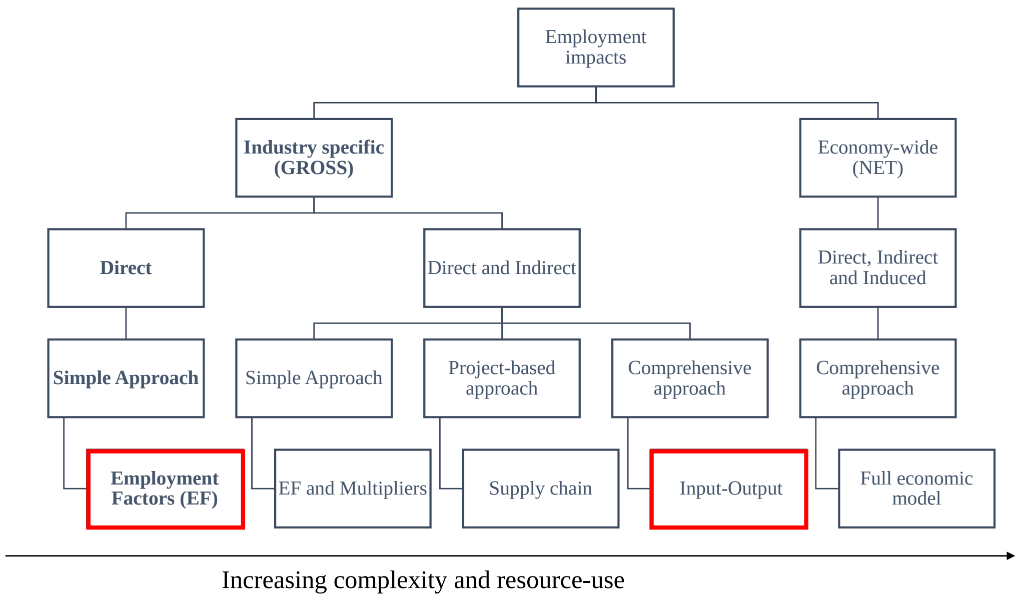

Figure 7: Approaches to study employment impact; Elaborated by IRENA (2014) based on Breitschopf et al. (2012).

Approach	Description	Advantages	Limitations
Analytical - Employment factor approach	Generally combine employment factors produced from literature and industry surveys with energy sector data produced from an energy model or IAM	High level of transparency and simplicity (Cameron and van der Zwaan, 2015)	• Reported employment factors for different technologies and activity can vary widely (Cameron and van der Zwaan, 2015) • Cannot calculate indirect employment impacts • Most studies of employment factors limited to OECD countries • Few studies with employment factors of conventional technologies
IO or CGE approaches		Allows for the consistent estimation of both direct and indirect effects due to inter-linkages between sectors	• Imply a large burden in terms of data collection, as they require detailed knowledge of how industries are linked to one another (Cameron and van der Zwaan, 2015) • Carries typical limitations of IO models: doesn't account for for time lags, homogeneity of outputs, high sectoral aggregation (doesn't resolve RE sectors), absence of economies of scale, invariance of technological coefficients and productivity, and missing interactions between prices and quantities (Markandya et al., 2016; Fragkos and Paroussos, 2018)

Table 1.2: Table showing differences between the two broad types of approaches to measure employment impacts.

The differences in methodological approaches, each with their advantages and limitations, and the scope of difference studies (direct, indirect, or induced employment) make comparison difficult. Even for studies using the same approach, there can a wide range of input values and key assumptions, making a one-to-one comparison difficult.

1.5 Structure of the thesis

The three research questions introduced in Section 1.3 form the basis of the three core chapters of the thesis. The linking of the core chapters to the conceptual framework (Section 1.2) is illustrated in Figure 8. A solid one-way arrow shows a direct relation to the elements within the classifier whereas a dashed one-way arrow shows an indirect relation. Thus, Chapter 2: "Reducing Stranded Assets through Early action in the Indian Power sector" explores techno-economics barriers emerging from the risk of stranded assets. Chapter 3: "Climate Policy accelerates structural changes in energy employment" investigates socio-economic and political barriers emerging from changes in energy employment, especially the loss of coal mining jobs. Chapter 4: "Early just transition opportunities for coal-bearing states of India" again explores political barriers emerging from unequal distribution of energy assets in the country. Lastly, Chapter 5 summarises the main findings of the three published studies, discusses their policy implications, identifies limitations, and suggests areas of future research work. The references to chapter 1 and chapter 5 are listed at the end of the thesis under 'References', while references to chapters 2, 3, and 4 are listed after each chapter.

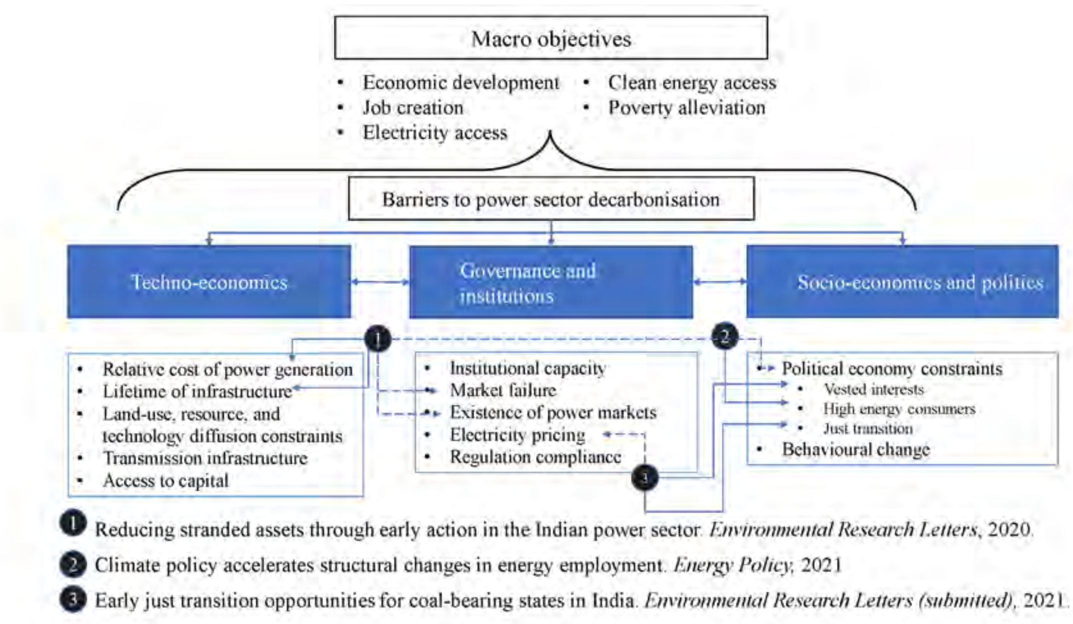

Figure 8: Objective and outline of the thesis, including where the different thesis chapters state in the conceptual framework. A solid one-way arrow shows a direct relation to the elements within the classifier whereas a dashed one-way arrow shows an indirect relation.

Chapter 2

Reducing stranded assets through early action in the Indian power sector[*]

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Reducing stranded assets through early action in the Indian power sector

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Keywords: carbon lock-in, coal, India, power, stranded assets, climate policy, Nationally determined contribution (NDC)

Supplementary material for this article is available online

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 (IEA 2018, Coal Swarm 2019), 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 supplementary information section 1 and figure S3 (stacks.iop.org/ERL/15/094091/mmedia) 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 (Unruh 2000, Erickson *et al* 2015). 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 (Erickson *et al* 2015, Johnson *et al* 2015, Bertram *et al* 2015a). Furthermore, cost reductions in alternative power technologies, especially renewables could render 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 (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 (IEA 2015, Shukla *et al* 2015, Byravan *et al* 2017, Das and Roy 2018, 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 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 (Clarke *et al* 2014, Bertram *et al* 2015a, 2015b, Luderer *et al* 2016, 2018), 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,

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

[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 10 years.

[3] Main features of India's (I)NDC- (i) Reduction in emissions intensity of its GDP by 33 to 35% 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).

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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.

2.1. 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 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)

2.2. 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 does not 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.

2.3. 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 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.[7] The diversity of modelling approaches and assumptions reflect the inherent uncertainty about drivers and determinants of social systems, and the comparison of results allows

[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).

[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.

[7] 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.

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.

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[8].	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.		

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).

2.4. 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

3.1.1. 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

[8] 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.

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

[10] http://www.iess2047.gov.in. The IESS Scenarios do not 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).

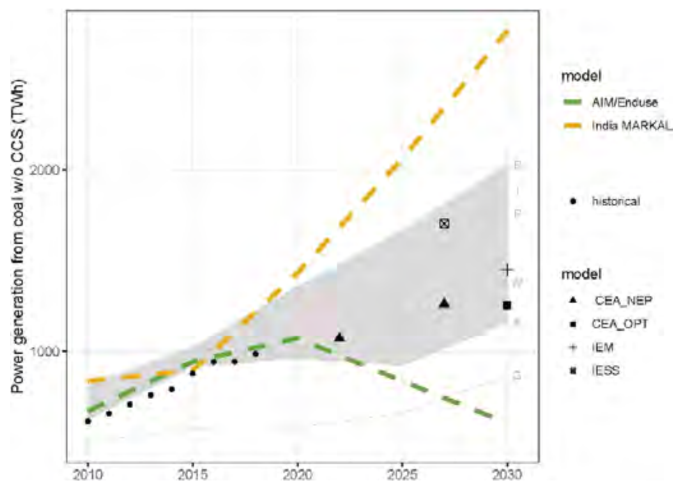

Figure 1. Power generation from Coal (2010 to 2030 in TWh) for the delayed scenario. The grey ribbon represents the spread from the global models (except GEM-E3, see SI section 7). The alphabets represent the first letter of the name of each global model. The coloured-dashed lines are the national models. 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.

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.

3.1.2. 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 2(a), 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 2(b)) with national (117–334 TWh) and global (151–312 TWh) projections broadly in line with projections from CEA (188 TWh in 2027).

3.1.3. Near-term projection of coal alternatives—gas

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]

[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).

[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) (only the year should be the link and coloured blue) ~ USD 1.6/ton CO2, can be labelled as a carbon tax, but is considered insignificant for our purposes.

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

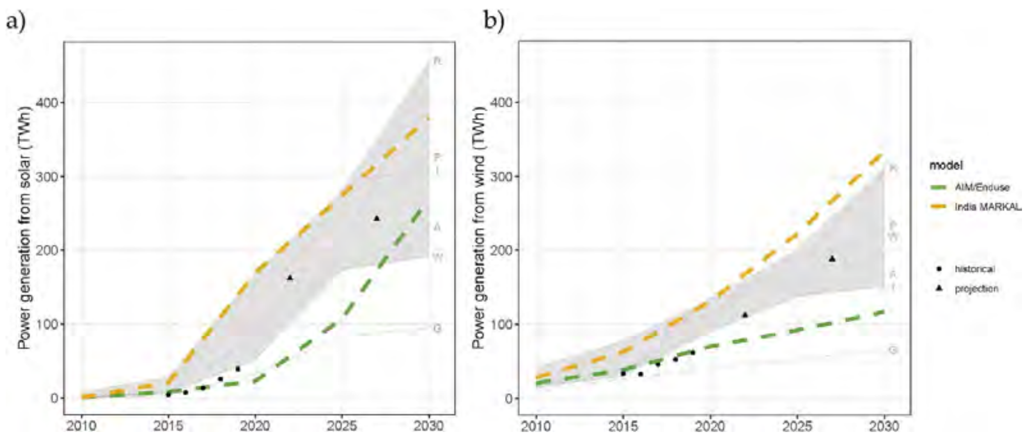

Figure 2. Power generation from (a) solar (a) and wind for the delayed scenario until 2030. The black dots represent historical values and the black triangles are projections from the CEA NEP. The latter include renewable targets mentioned in the NDC (175 GW of installed renewable capacity by 2022) and 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.

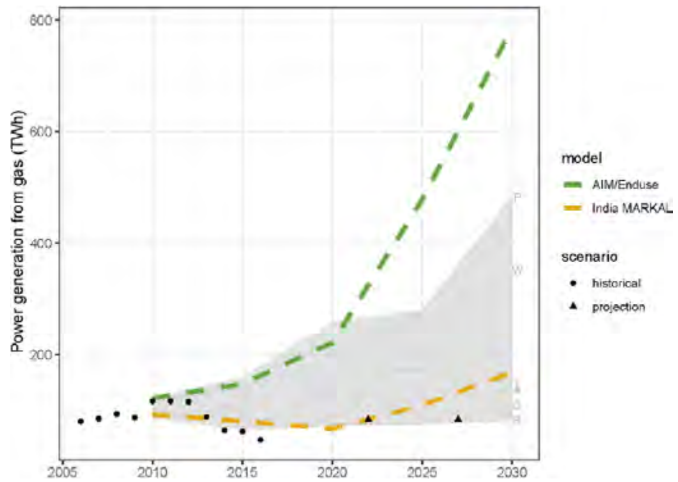

Figure 3. Power generation from gas (TWh) from 2005–2030. Black dots are historical values and black triangles are projections from CEA. The grey ribbon represents the range across the global IAMs while the dashed coloured lines are the national models.

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 (Sen 2015, Chaturvedi *et al* 2018).

3.1.4. 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

[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.

in 3.1). Thereafter, the global IAMs achieve cost-effective mitigation (through a carbon price) under a carbon budget constraint up to 2100. On 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.

3.2.1. 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) figures 4(a) and (b) 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 4(c) 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 4(a) 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 4(b))—shows that the magnitude of stranded capacity from plants yet to be built and currently installed plants would be similar.

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

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).

3.2.2. 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.

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 does not 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.

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

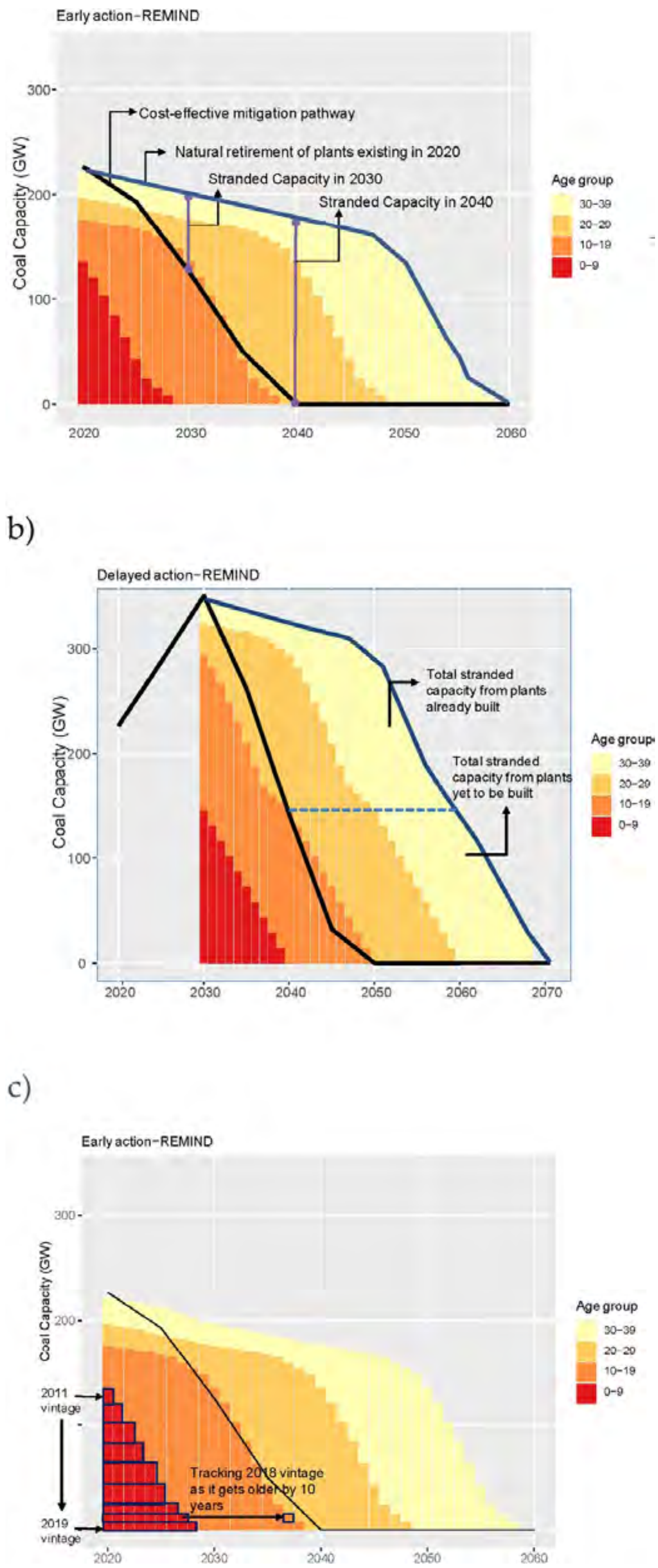

Figure 4. Coal capacity development assuming natural retirement (dark blue line) and coloured according to age-group. Black lines are cost-effective pathways (calculated from the generation data, see SI section 10 for an explanation. Results for (a) Early action and (b) Delayed action for REMIND. Results 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. (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.

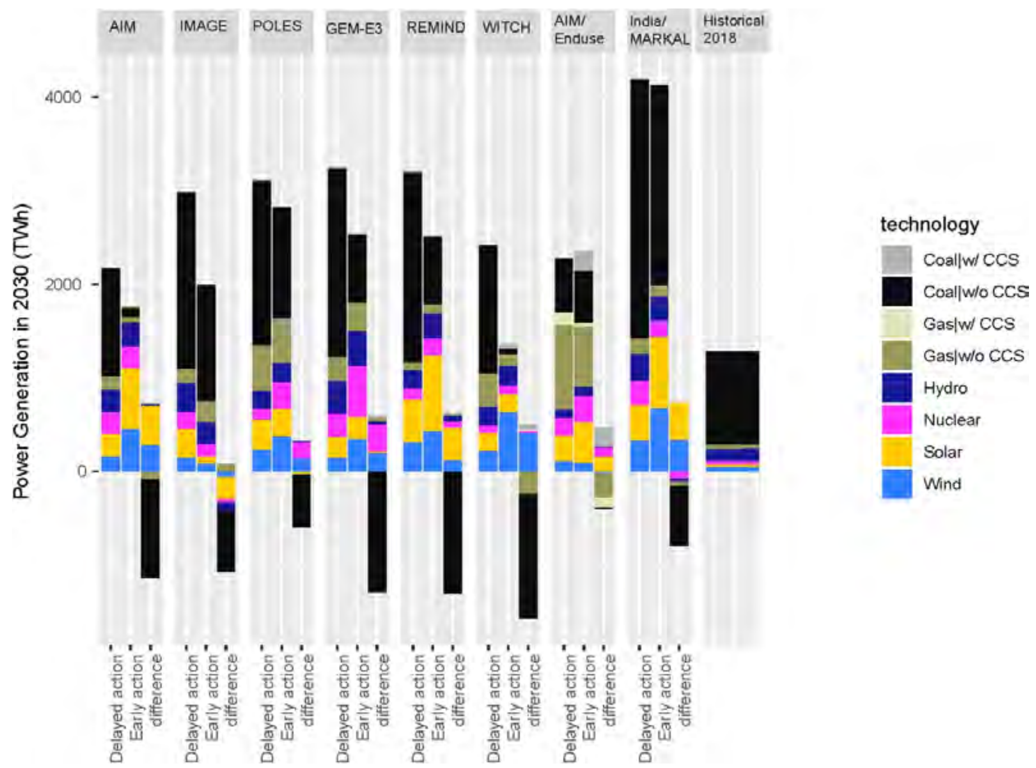

Figure 5. Power generation in 2030 from different sources for the two scenarios—Delayed and Early action, as well as the difference of the two scenarios. The distribution of power from different sources in 2018 is shown in the extreme right column.

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 (Hirth *et al* 2015, Palchak *et al* 2017, Scholz *et al* 2017, Chaturvedi *et al* 2018), 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.

In 2015, a new legislation was introduced requiring all coal power plants to control the concentration

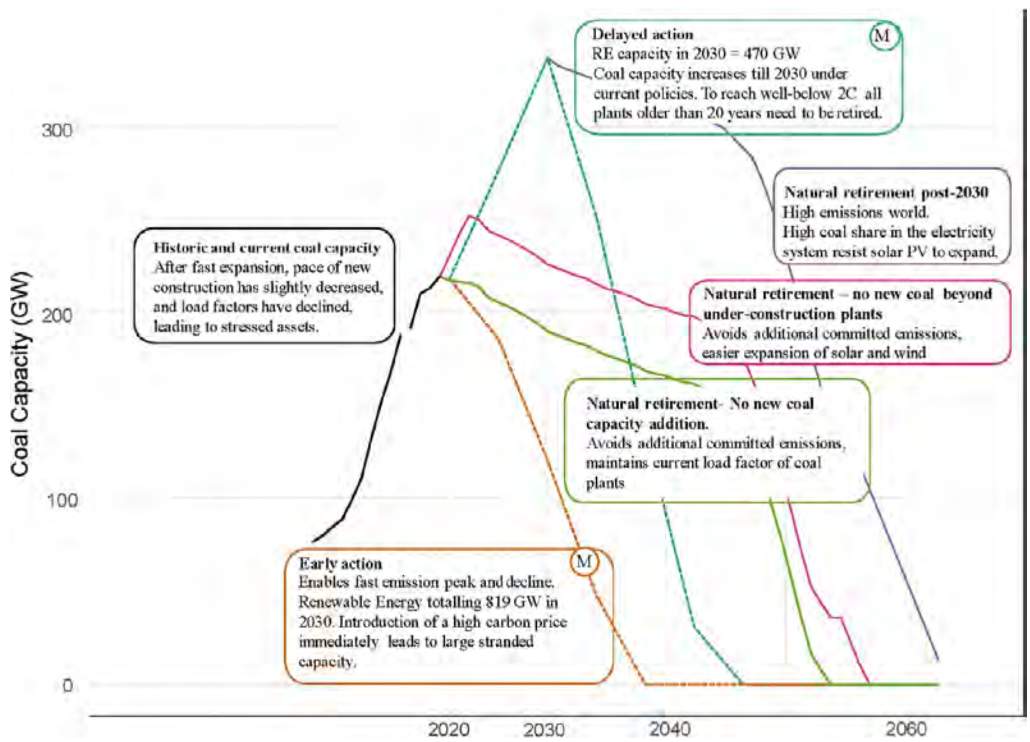

Figure 6. Descriptions and implications of various scenarios of coal capacity development in India. 'M' denotes modelling result, the example shown is from the global model REMIND. The Purple line is deduced from the 2030 generation value in REMIND, while the green and purple are based on bottom-up data.

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 (Murdock *et al* 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 1.5 C 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, Vishwanathan *et al* 2018, Tang *et al* 2019), nor does it include 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.

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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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Reducing stranded assets through early action in the Indian power sector

Supplementary Information

Contents

1 Coal in the Indian power sector

The power sector contributes to 32% (~0.92 Gt) of the total CO2eq emissions (excluding Landuse) in India (IEA, 2015). As of March 2017, the share of coal in total power capacity and generation was 58% and 76% respectively (Central Electricity

Authority, 2018a), making India one of the countries with highest-share of coal in the power sector (Central Electricity Authority, 2018b; World Bank, 2019). In the last 10 years, power generation has grown at an average rate of 5.7% (Ministry of Power, 2019), mostly through rapid addition of coal plants. The Indian coal fleet is new with around 68% of the current capacity having an age of less than 10 years (built in 2008 or later) (Coal Swarm, 2019).

2 Bottom-up data

Bottom-up data on various historical and future/projected variables has been principally taken from two sources: The National Electricity Plan, 2018 by the Central Electricity Authority (CEA) and the CoalSwarm Global Plant Tracker, 2019.

One of the functions of the Central Electricity Authority (CEA), under the Ministry of Power, is providing policy advice to the Government of India for forming policies in the power sector (Central Electricity Authority, 2018). It publishes biannually, a National Electricity Plan (NEP), projecting the future electricity demand and technologies that can optimally provide this demand, considering the current policies and targets and the status of various technologies (indigenous resources, alternate uses, costs). Bottom-up data in this paper has heavily used the National Electricity Plan published in January 2018. Information on the current capacity and projections of the required capacity for different technologies has been summarised in Table S1 . Note that CEA only tracks utility-scale plants, so captive plants (power plants set up by industries for own consumption) are not included in these numbers.

In their draft National Electricity Plan (NEP) (Dec. 2016), the CEA projected that India would need no new coal plants (in 2022 - 2027) apart from those under-construction at that time (50 GW). However, in the actual NEP (Central Electricity Authority, 2018a), they revised the numbers – 94 GW of new coal capacity would be needed in the period 2017-2027 and 46 GW would need to be retired (inefficient plants over 25 years which cannot comply with the new environmental regulations). Although the NEP provides no projections on required coal-power capacity beyond 2027, it mentions 88.4 GW of plants under various stages of planning, thus also implying new coal-power capacity beyond 2027.

	Current Capacity (MW) Updated 31.03.2019	Capacity March 2017 (MW)	Capacity Addition (MW) 12th plan (2012-2017)	Projected Capacity Addition (2017-22) (MW)	Projected retirement (2017-2022) (MW)	Installed Capacity in 2022 (MW)	Projected Capacity Addition (2022-2027) (MW)	Projected retirement (2022-2027) (MW)	Installed Capacity in 2027 (MW)
Coal	194445	197000	83560	47855	22716	217302	46420	25572	238150
Lignite	6360		1290						
Diesel	637	700							
Gas	24937	26167	6880.5	406		25735			
Hydro	45399	44479	5479	6823		51301	12000		
Nuclear	6780	6780	2000	3300		10080	6800		
Solar	28181	12300	32741	87711		175000	50000		275000
Wind	35626	32280		27720			40000		
Biomass -cogen	9104	8295		1705			7000		
Small-Hydro	4593	4380		620			3000		
Waste to Energy	138	138		0			0		
TOTAL	**356100**			176140			165220		

Table S1: Current capacity and projections of future capacity for different power generation technologies. Source: (Central Electricity Authority, 2018a, 2018c)

Coal Swarm publishes the Global Coal Plant Tracker roughly every six months, tracking operating, under-construction and planned coal plants all over the world. This paper uses the edition published in January 2019.

Development of coal power plants in India

The development of coal plants in India from 2015-2019 is provided in Figure S1. The figure shows that although the overall coal capacity has increased in the last five years (dark green), the momentum of coal plant construction is slowing down - the number of cancelled plants has increased (red), and the planned plants are decreasing (blue). In 2018, less than 3 GW of plants were permitted for construction, compared to an annual average of 31 GW from 2008 to 2012, and 13 GW from 2013 to 2017 (Shearer et al., 2019).

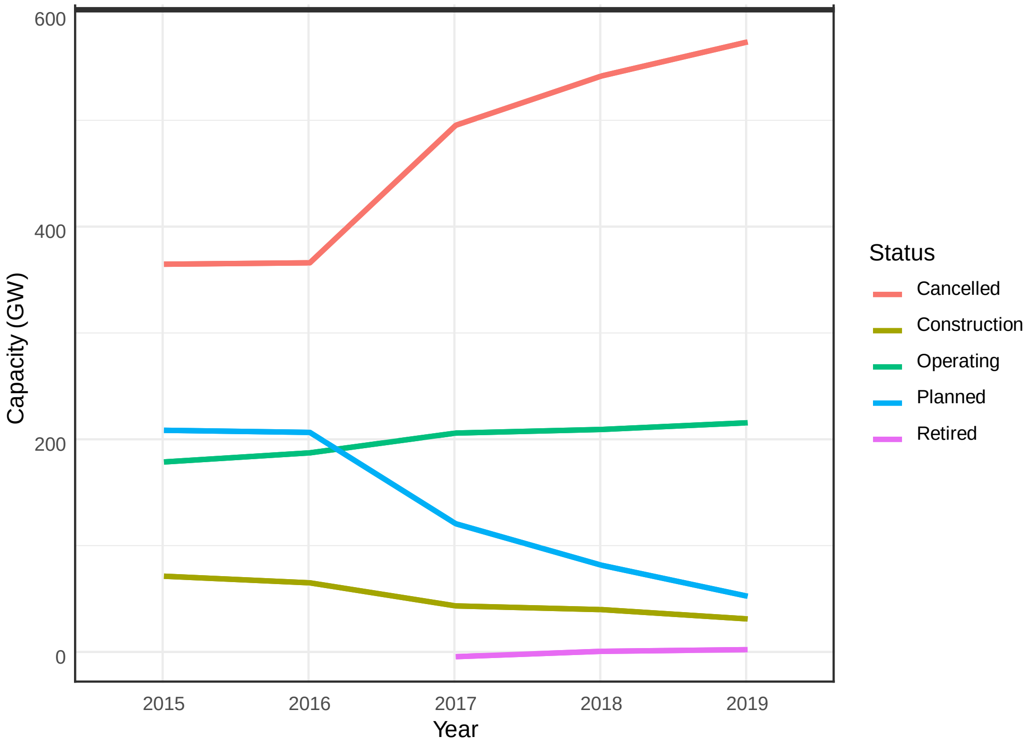

Figure S1 Capacity of unabated coal plants of different status - cancelled (red), under-construction (dark green), operating (green), planned (blue), and retired (pink), with Year. Data from the CoalSwarm Database, 2019.

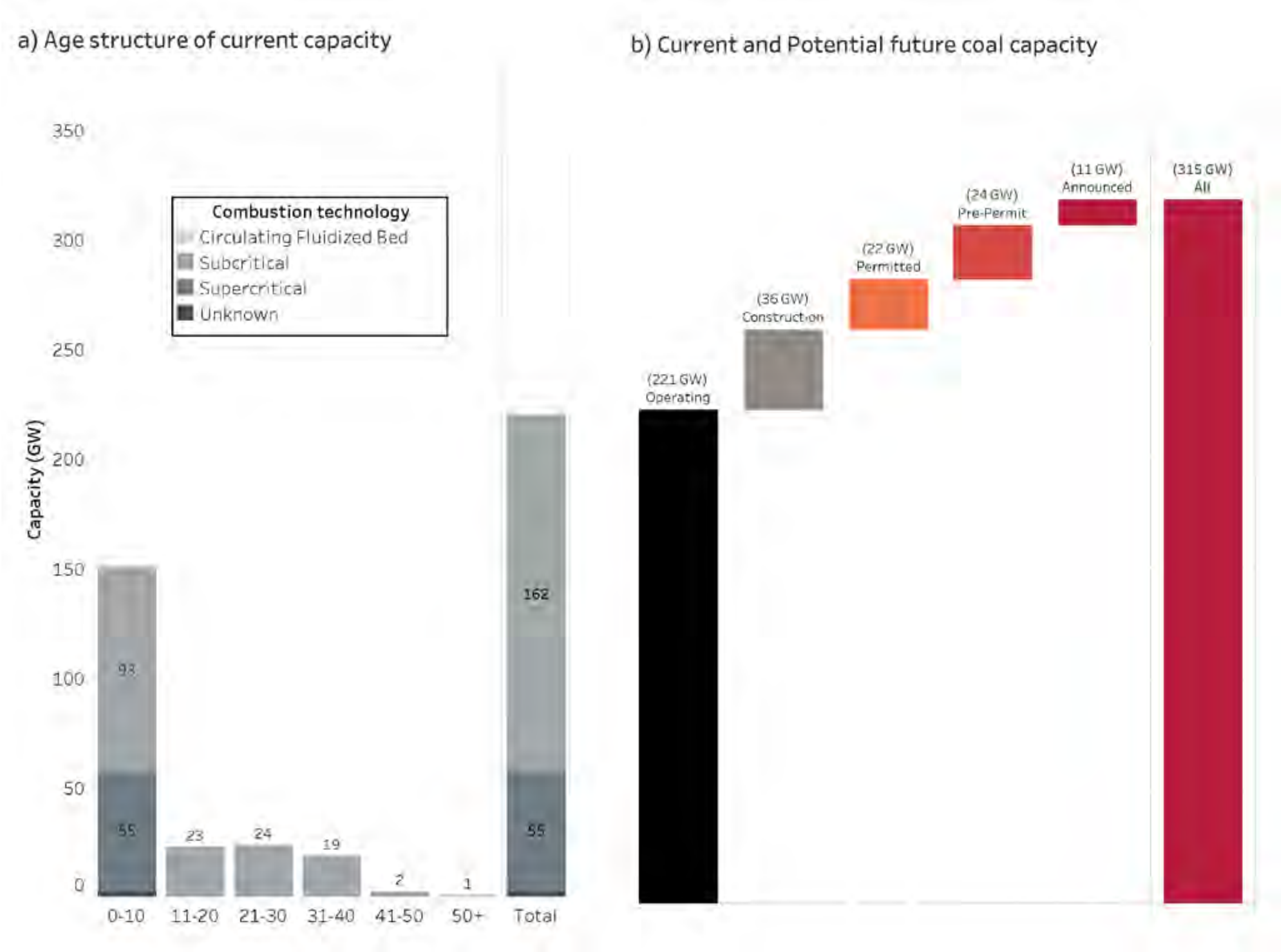

Figure S2 a) Current capacity differentiated on age-group (y-axis) and combustion technology (colour). b) Current and future coal capacity from (Coal Swarm, 2019).

3 Current and future potential emissions from coal power

Status	Capacity (as of 2017) [1] GW – (a)	Plant Load factor (b)	Generation (GWh) a*b*8760 (d)	Emission factor (t CO2/ GWh) (e)	Lifetime/ Remaining lifetime (years) (f)	Lifetime emissions (Gt CO2) d*e*f
Operating	211	0.6[2]	1035081	0.92[3]	25	24
Under-Construction	48.4	0.6	254390	0.8[4]	40	8
Planned	90.4[5]	0.6	475142	0.8	40	15

Table S2 Calculation of the lifetime emissions of operating, under-construction, and planned coal plants in India (as of end 2017)

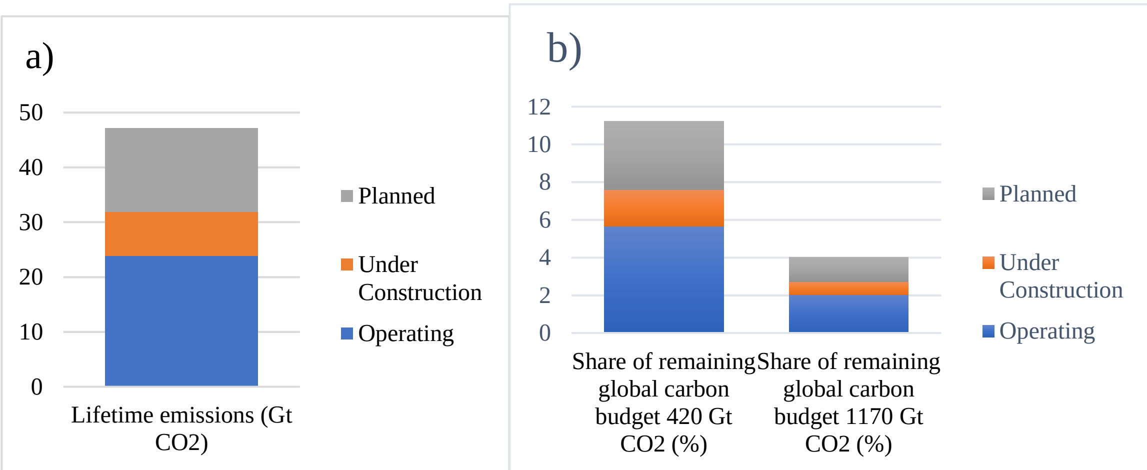

Figure S3 a) Lifetime emissions (in Gt CO2) of different classes of coal plants (operating -blue, under construction - orange, and planned-grey) and b) their share in the remaining global carbon budget (66% chance) for 1.5° C and 2° C (in %). Data from Coal Swarm, 2019. Assuming technical lifetime of 40 years.

[1] Data from Coal Swarm, 2019. The status of the capacities in 2017 have been taken to use the remaining carbon budget figures which are given from 1.1.2018 in (Rogelj et al., 2018)
[2] CEA estimates that net effect of renewable capacity addition (through the 175 GW RE target), coal capacity currently under-construction, and some plants retiring, the Plant Load factor (PLF) of coal power plants will decrease from the current – 0.6 to 0.56 in 2021-22 and then again increase to 0.6 in 2026-2027. The PLF is assumed to be 0.6 till the end of the lifetime of the plant.
[3] Table 32, Nierop and Humperdinck, 2018.
[4] Assuming future coal plants to be supercritical.
[5] Planned plants include those under the categories of "Pre-permit" and "Permit", but excludes "Announced" as it represents a more realistic figure of future capacity addition.

4 High-Impact Policies and NDC of India

The following policies were identified as most important for GHG (greenhouse gas) emissions reduction in India:

Electricity and heat

- *National Solar Mission (Phase I and II):* Sets a target of 20 GW installed capacity of solar electricity by 2022. Revised to 100 GW by 2022.
- *National Wind Mission*: Sets a target of 38.5 GW wind power by 2022. Revised to 60 GW by 2022.
- *Government Assistance for Small Hydropower Stations:* Sets a target of 6.5 GW small hydro installed capacity by 2022, supported by economic incentives.
- *Central Financial Assistance (CFA) for Biogas Plants:* Sets a target of 10 GW biogas installed capacity by 2022, supported by economic incentives.
- *Renewable Purchase Obligations*: Mandates electricity producers to purchase a percentage of the total generation from renewables. The national target was set at 6% in 2010/11 and is to be progressively increased by 1% each year, reaching 15% by 2020.
- *Twelfth Five Year Plan (2012–2017):* Use of supercritical power plants as part of the focus area 'Advanced coal technologies', resulting in efficiency improvements equivalent to a power plant standard of 840 gCO_2/kWh.

Industry

- *Perform, Achieve, Trade (PAT) Scheme*: Sets a target of 2.2 Mtoe reduction in total industrial energy consumption by 2015 compared to BAU and 7 Mtoe by 2020.

Transport

- *National Electric Mobility Mission Plan*: Sets a target of 6-7 million annual sales of hybrid and electric vehicles from 2020 onwards.
- *Vehicle energy consumption standards*: Light-duty vehicle GHG emissions standards are 130 gCO_2/km by 2016 and 113 gCO_2/km by 2021.
- *National Policy on Biofuels:* Sets a mandatory ethanol blending volume of 5% in petrol from 2007, and 10% from 2008. Indicative targets are 20% for both biodiesel blend in diesel and bioethanol blend in petrol, from 2017 onwards.

Agriculture and forestry

- *National Green India Mission (GIM):* Sets a target of 5 million ha forest area increase by 2030 compared to 2005, expected to lead to 13 MtCO2e emissions reduction for the same period.

NDC of India

- To reduce the emissions intensity of GDP by 33 to 35 percent by 2030 from its 2005 level.
- To achieve about 40 percent cumulative electric power installed capacity from non- fossil fuel-based energy resources by 2030 with the help of transfer of technology and low-cost international finance including from Green Climate Fund (GCF).
- To create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.

5 Implementation of global and national scenarios

The scenarios in this study are differentiated by i) short-term climate and energy policies, and ii) attained long-term targets (represented via mid-century carbon budgets for the national models, i.e., cumulated 2011-2050 CO2 emissions from fossil-fuel combustion and industrial processes, and carbon budgets from 2011-2100 for global models). Both national and global model scenarios have been selected from a larger scenario set developed within the CD-Links project (from Kriegler et al., in review) (http://cdlinks.org/).

Carbon budgets

The country-specific CO2 budgets were determined in a discourse between national and global modeling teams. The starting point of this discourse were the ranges of regionalized budget estimates from global cost-effective pathways with a 1000 Gt CO2 cumulative budget 2011-2100, as shown in Table S3 (if emissions reductions after 2020 are made where they are cheapest). For the case of the India, the two national models were not able to reach the low budget due to specific assumptions on near-term investments and lifetime of infrastructure, so that the budget numbers were adjusted upwards, allowing also for a differentiation between the two models so that each model comes close to its lowest possible budget number in the “low” scenarios.

	Carbon budget for India (Gt CO2)	
	Early action	Delayed action
Global models	25-86	32-91
IIM-AIM	~ 115	~140
India-Markal*	187	191

Table S3 Budget ranges from preliminary global least-cost pathways with strengthening after 2020 that were used to inform the choice of national budgets, although some adjustment was made after initial scenario tests.

National scenarios

The two scenarios produced by **national** models discussed in this paper are defined as follows:

1. **Early action scenario**: A scenario representing the current energy and climate policy landscape of India. Most of the policies are defined until 2020, followed by a long-term target in terms of a national carbon budget for the period 2011-2050.

2. **Delayed action scenario:** In addition to the policies represented in the "Early action" scenario, this scenario incorporates for all policies or targets formulated in the national NDC submission until 2030, followed by a carbon budget constraint thereafter. Unlike the global models which have same carbon budgets, the budgets for the two national models are different with MARKAL having a higher budget than AIM/Enduse.

Until 2020, the CO2 emissions are assumed to be the same in both the scenarios. Both scenarios used in the study represent the deepest mitigation scenarios, out of several scenarios defined by cumulative CO2 emissions from 2011 – 2050. Thus, the policies in early and delayed action serve as a lower bound for the targets and overachievement is possible.

Global scenarios

The scenarios for global models are similar apart from that they perform cost-effective mitigation (pursue emissions reductions where and when they are cheapest), in 2020 for early action and 2030 for delayed action, using a carbon budget of 1000 GtCO2 for **well below 2°C** pathway (representing a 66% likelihood of staying below 2°C during the 21st century)

In the delayed scenario, for the period between 2021 and 2030, utilities and plant operators have limited foresight, making decisions based on current and NDC policies. Post-2030, decisions are no longer myopic, and foresight is extended to 2050 and 2100 for national and global models respectively.

6 Model Descriptions

The following section provides tables on "quick information" of each model used in the study while the text below them describes their structure in detail. They are based on the Supplementary Information of (Kriegler et al., 2019)).

National Models

Model name	Institution	Model type	Sector coverage	Coverage of GHG and aerosol emissions	Carbon dioxide removal technologies
AIM-India (Kainuma et al., 2003; Shukla et al., 2004; Vishwanathan et al., 2017)	IIM, India	Recursive dynamic, partial equilibrium	Energy supply, Industry, Transport, Residential, Commercial & Agriculture (energy use only)	CO_2 Emissions	CCS
India-MARKAL (Sachs et al., 2014; Sharma, S., & Kumar, A. (Eds.), 2016; The Energy and Resources Institute, New Delhi, India,	TERI, India	Dynamic least cost optimization	Energy supply, Agriculture, Domestic, Industry, Buildings, Transport	CO_2 Emissions only	-

2015; WWF-India and The Energy and Resources Institute, New Delhi, India, 2013)					

Table S4 National model characteristics. More detailed descriptions of each of these models can be found in the text below.

AIM/Enduse 3.0 (India) is a bottom-up optimization model that provides a techno-economic perspective at national level with sectoral granularity. Built on a disaggregated, sectoral representation of the economy, it provides a detailed characterization of technologies and fuel based on their availability, efficiency levels and costs. It estimates the current and future energy consumption and GHG emissions of all sectors. It uses linear programming to provide a set of technologies that will meet the exogenous service demand at the least cost while satisfying techno-economic, emissions- and energy-related constraints.

The model has been set up for five major sectors and their respective services, technologies, reference years and discount rates. These sectors are agriculture, industry, power, residential (including commercial) and transportation. Multiple services in each sector have been examined to provide a better understanding of the sector. For example, fifteen industries have been selected to represent the industry sector, while passenger and freight characterize travel demand in the transport sector. The model comprises of over 450 existing, advanced, and futuristic energy supply and demand technologies.

TERI's India MARKAL model has been continuously developed over the past two decades and exists as a rich and disaggregated database of energy demand and supply technologies representing India's energy system. The model has been used to develop and examine scenarios to identify and prioritise choices for mitigation and energy efficiency and explore the implications of different emissions constraints. The model has been used to inform policy making within the country (providing inputs for India's NDCs) as well as across a number of national and international studies related with energy security, mitigation and climate change. The model has been used across several studies in the past to analyse implications for India's energy sector. These include Energising India – Towards a Resilient and Equitable Energy System(Bery et al., 2016), Air Pollutant Emissions Scenario for India (Sharma, S., & Kumar, A. (Eds.), 2016), Energy Security Outlook (The Energy and Resources Institute, New Delhi, India, 2015), Pathways to deep decarbonization (Sachs et al., 2014), and The Energy Report- India 100% Renewable Energy by 2030 (WWF-India and The Energy and Resources Institute, New Delhi, India, 2013).

The MARKAL (MARket ALlocation) model is a bottom up dynamic linear programming cost optimization model depicting energy supply, conversion and consumption across demand sectors of a complete generalised energy system. The MARKAL family of models is unique, with applications in a wide variety of settings and global technical support from the international research community. The optimization routine used in the model's solution selects from each of the sources, energy carriers, and transformation technologies to produce the least-cost solution, subject to a variety of constraints. The user defines technology costs, technical characteristics (e.g., conversion efficiencies), and energy service demands.

The current model database, developed by Ritu Mathur, Atul Kumar, Aayushi Awasthy, Sugandha Chauhan, Kabir Sharma, Swapnil Shekhar and Prakriti Prajapati is set up over a 50 year period extending from 2001-2051 at five-yearly intervals originally intended to coincide with the Government of India's Five-Year plans. In the model, the Indian energy sector is disaggregated into five major energy consuming sectors, namely, agriculture, commercial, industry, residential and transport sectors. End use demands for each of the sectors are derived exogenously using excel based/econometric models.

On the supply side, the model considers the various energy resources that are available both domestically and from abroad for meeting various end-use demands. These include both the conventional energy sources (coal, oil, natural gas, and nuclear) as well as the renewable energy sources (hydro, wind, solar, biomass etc.). The availability of each of these fuels is represented by constraints on the supply side.

The relative energy prices of various forms and source of fuels play an integral role in capturing inter-fuel substitutions within the model. Furthermore, various conversion and process technologies characterized by their respective investment costs, operating and maintenance costs, technical efficiency, life etc. that meet the sectoral end-use demands are also incorporated in the model. In case of technologies that are specific to India, country specific costs are included (capital costs and O&M costs), while globally existing technologies have made use of international sources of data as well. Cost reduction in future in the emerging technologies has also been assumed based on an understanding of the particular technology development.

The database in its current form incorporates 47 end-uses spanning more than 350 technologies. While the demands are set up in line with basic driving parameters such as projected population, urbanization and GDP, the various scenarios include emission constraints and/or reflections of policies and measures that provide varying priorities to alternative energy forms over the modelling timeframe in order to meet the requirements of the CD-LINKS scenarios.

Global Models

Model name	Institution	Model type	Sector coverage	Coverage of GHG and aerosol emissions	Carbon dioxide removal technologies
AIM/CGE (Fujimori, Hasegawa, & Masui, 2017; Fujimori, Hasegawa, Masui, et al., 2017; Fujimori, Masui, et al., 2017)	NIES, Japan	Recursive dynamic, general equilibrium	Energy supply, Buildings, Industry, Transport, AFOLU	full basket of greenhouse gases, precursors and aerosols	BECCS (for electricity, liquids), Afforestation
GEM-E3 (Capros et al., 2014, 2016; E3MLab, 2016; Karkatsoulis et al., 2017)	E3M-Lab, ICCS, Greece	Recursive dynamic, general equilibrium	All sectors apart from AFOLU	full basket of greenhouse gases	N/A
IMAGE/TIMER (Stehfest et al., 2014)	PBL, The Netherlands	Recursive dynamic, partial equilibrium	Energy supply, Buildings, Industry, Transport, AFOLU	full basket of greenhouse gases, precursors and aerosols	BECCS (for electricity, biofuels and hydrogen production)
REMIND-MAgPIE (Kriegler et al.,	PIK, Germany	Perfect foresight, general equilibrium	Energy supply, Buildings, Industry,	full basket of greenhouse gases,	BECCS (for electricity, biofuels and

2017; Luderer et al., 2013, 2015)			Transport, AFOLU	precursors and aerosols	hydrogen production)
WITCH (Bosetti et al., 2006a; Emmerling, Drouet, Reis, Bevione, Berger, Bosetti, Carrara, Cian, Enrica, et al., 2016)	FEEM, Italy	Perfect foresight, general equilibrium	Energy supply, Buildings, Industry, Transport, AFOLU	CO2, CH4, N2O, flourinated gases and SO2 aerosols	BECCS (for electricity production)
POLES (Keramidas et al., 2017)	JRC, Spain	Recursive dynamic, partial equilibrium	Energy supply, Buildings, Industry, Transport, AFOLU	full basket of greenhouse gases, precursors and aerosols	CCS for electricity, biofuels, hydrogen production, industry; Net carbon sinks in LULUCF

Table S5 Global model characteristics. More detailed descriptions of each of these models can be found in the text below.

AIM/CGE (Fujimori, Hasegawa, & Masui, 2017; Fujimori, Hasegawa, Masui, et al., 2017; Fujimori, Masui, et al., 2017) is a one-year-step recursive-type dynamic general equilibrium model that covers all regions of the world. The AIM/CGE model includes 17 regions and 42 industrial classifications. For appropriate assessment of bioenergy and land use competition, agricultural sectors are also highly disaggregated. Details of the model structure and mathematical formulae are described by(Fujimori, Hasegawa, & Masui, 2017). The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. Energy transformation sectors input energy and value added are fixed coefficients of output. They are treated in this manner to deal with energy conversion efficiency appropriately in the energy transformation sectors. Power generation values from several energy sources are combined with a Logit function. This functional form was used to ensure energy balance because the CES function does not guarantee an energy balance. Household expenditures on each commodity are described by a linear expenditure system function. The parameters adopted in the linear expenditure system function are recursively updated in accordance with income elasticity assumptions. In addition to energy-related CO_2, CO_2 from other sources, CH_4, N_2O, and fluorinated gases (F-gases) are treated as GHGs in the model. Energy-related emissions are associated with fossil fuel feedstock use. The non-energy-related CO_2 emissions consist of land use change and industrial processes. Land use change emissions are derived from the forest area change relative to the previous year multiplied by the carbon stock density, which is differentiated by Global AEZs (Agro-Ecological Zones). Non-energy-related emissions other than land use change emissions are assumed to be in proportion to the level of each activity (such as output). CH_4 has a range of sources, mainly the rice production, livestock, fossil fuel mining, and waste management sectors. N_2O is emitted as a result of fertilizer application and livestock manure management, and by the chemical industry. F-gases are emitted mainly from refrigerants used in air conditioners and cooling devices in industry. Air pollutant gases (BC, CO, NH_3, NMVOC, NO_X, OC, SO_2) are also associated with fuel combustion and activity levels. Essentially, emissions factors change over time with the implementation of air pollutant removal technologies and relevant legislation.

GEM-E3 model is a hybrid, recursive dynamic general equilibrium model that features a highly detailed regional and sectoral representation (Capros et al., 2014, 2016; E3MLab, 2016; Karkatsoulis et al., 2017). The model provides insights on the macroeconomic and sectoral impacts of the interactions of the environment, the economy and the energy system. GEM-E3 allows for a consistent comparative analysis of policy scenarios, ensuring that in all scenarios, the economic system remains in general equilibrium. The model has been calibrated to the latest statistics (GTAP 9, IEA, UN, ILO) while Eurostat statistics have been included instead of the GTAP IO tables for the EU Member States. The GEM-E3 model simultaneously calculates the equilibrium in goods and service markets, as well as in the labor and capital markets based on an optimization of objective functions (welfare for households and cost for firms), and includes projections of: full Input-Output tables by country/region, national accounts, employment, balance of payments, public finance and revenues, household consumption, energy use and supply, GHG emissions and atmospheric pollutants. The model is modularly built allowing the user to select among a number of alternative closure options and market institutional regimes depending on the issue under study. Production functions feature a CES structure and include capital, labour, energy and intermediate goods, while the formulation of production technologies happens in an endogenous manner allowing for price-driven derivation of all intermediate consumption and the services from capital and labour. The model simulates consumer behavior and explicitly differentiates durable and disposable goods and services. The simulation framework is dynamic, recursive over time, linked in time though the accumulation of capital and equipment. The GEM-E3 regions are linked via endogenous bilateral trade in line with the Armington assumption. This model version features 19 countries/regions, explicitly representing the G-20 members apart from those that are Members of the European Union, as EU28 is represented as one region. The sectoral detail of this model version is high, with 39 separate economic activities, including a distinct representation of the sectors that manufacture low-carbon power supply technologies, electric cars and advanced appliances. In addition, the model includes a detailed representation of the power generation system (10 power technologies) and a highly detailed transport supply module (private and public transport modes). Key novel features of the GEM-E3 model include the involuntary unemployment and an explicit representation of the financial sector. In addition, the GEM-E3 environmental module covers all GHG emissions and a wide range of abatement options, as well as a thoroughly designed carbon market structure (e.g. grandfathering, auctioning, alternative recycling mechanisms) providing flexibility instruments that allow for a variety of options of emission abatement policies.

IMAGE 3.0 is a comprehensive integrated assessment framework, modelling interacting human and natural systems (Stehfest et al., 2014). The IMAGE framework is suited for assessing interactions between human development and the natural environment, including a range of sectors, ecosystems and indicators. The impacts of human activities on the natural systems and natural resources are assessed and how such impacts hamper the provision of ecosystem services to sustain human development. The model framework is suited to a large geographical (usually global) and temporal scale (up to the year 2100).

The IMAGE framework identifies socio-economic pathways, and projects the consequences for energy, land, water and other natural resources, subject to resource availability and quality. Impacts such as air, water and soil emissions, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections. Within the IAM group, different types of models exist, and IMAGE is characterised by relatively detailed biophysical processes and a wide range of environmental indicators.

The IMage Energy Regional model (TIMER) has been developed to explore scenarios for the energy system in the broader context of the IMAGE framework. Similar to other IMAGE components, TIMER is a simulation model. The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states. TIMER includes 12 primary energy carriers in 26 world regions and is used to simulate long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions, together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia and learning-by-doing in capital stocks, depletion of the resource base and trade between regions.

The **POLES** (Prospective Outlook on Long-term Energy Systems) model(Keramidas et al., 2017) is a global partial equilibrium simulation model of the energy sector with an annual step, covering 38 regions world-wide (G20, OECD, principal energy consumers) plus the EU. The model covers 15 fuel supply branches, 30 technologies in power production, 6 in transformation, 15 final demand sectors and corresponding greenhouse gas emissions. GDP and population are exogenous inputs of the model. The model can provide insights of the evolution of global and local technology developments. The model can assess the market uptake and development of various new and established energy technologies as a function of changing scenario conditions. The global coverage allows an adequate capture of the learning effects that usually occur in global markets(Criqui et al., 2015). The model represents the adjustments of energy supply and demand to prices, while accounting for delayed reaction. POLES can also assess the global primary energy markets and the related international and regional fuel prices under different scenario assumptions. To this end, it includes a detailed representation of the costs in primary energy supply (in particular oil, gas and coal supply), for both conventional and unconventional resources. Major countries for the oil, coal and gas markets are represented.

The model can therefore be used to analyse the impacts of energy and climate policies, through the comparison of scenarios concerning possible future developments of world energy consumption and corresponding GHG emissions under different assumed policy frameworks[74]. Policies that can be assessed include: energy efficiency, support to renewables, energy taxation/subsidy, technology push or prohibition, access to energy resources, etc.

Mitigation policies are implemented by introducing carbon prices up to the level where emission reduction targets are met: carbon prices affect the average energy prices, inducing energy efficiency responses on the demand side, and the relative prices of different fuels and technologies, leading to adjustments on both the demand side (e.g. fuel switch) and the supply side (e.g. investments in renewables). Non-CO2 emissions in energy and industry are endogenously modelled with potentials derived from literature (marginal abatement cost curves). Air pollutants are also covered (SO2, NOx, VOCs, CO, BC, OC, PM2.5, PM10, NH3) thanks to a linkage with the specialist GAINS model. Projections for agriculture, LULUCF emissions and food indicators are derived from the GLOBIOM model (dynamic look-up of emissions depending on climate policy and biomass-energy use), calibrated on historical emissions and food demand (from UNFCCC, FAO and EDGAR). A full documentation of POLES is available at http://ec.europa.eu/jrc/poles.

REMIND (Kriegler et al., 2017; Luderer et al., 2013, 2015) models the global energy-economy-climate system for 11 world regions and for the time horizon until 2100. For the present study, REMIND in its version 1.7 was used. REMIND represents five individual countries (China, India, Japan, United States of America, and Russia) and six aggregated regions formed by the remaining countries (European Union, Latin America, sub-Saharan Africa without South Africa, Middle East / North Africa / Central Asia, other Asia, Rest of the World). For each region, intertemporal welfare is optimized based on a Ramsey-type macro-economic growth model. The model explicitly represents trade in final goods, primary energy carriers, and in the case of climate policy, emission allowances and computes simultaneous and intertemporal market equilibria based on an iterative procedure. Macro-economic production factors are capital, labor, and final energy. REMIND uses economic output for investments in the macro-economic capital stock as well as consumption, trade, and energy system expenditures.

By coupling a macroeconomic equilibrium model with a technology-detailed energy model, REMIND combines the major strengths of bottom-up and top-down models. The macro-economic core and the energy system module are hard-linked via the final energy demand and costs incurred by the energy system. A production function with constant elasticity of substitution (nested CES production function) determines the final energy demand. For the baseline scenario, final energy demands pathways are calibrated to regressions of historic demand patterns. More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy.

REMIND uses reduced-form emulators derived from the detailed land-use and agricultural model MAgPIE(Lotze-Campen et al., 2008; Popp et al., 2014) to represent land-use and agricultural emissions as well as bioenergy supply and other land-based mitigation options. Beyond CO_2, REMIND also represents emissions and mitigation options of major non-CO_2 greenhouse gases (EPA, 2013; Strefler et al., 2014).

WITCH-GLOBIOM (World Induced Technical Change Hybrid) is an integrated assessment model designed to assess climate change mitigation and adaptation policies. It is maintained and developed at the RFF-CMCC European Institute on

Economics and the Environment (EIEE). It is a global integrated assessment model with two main distinguishing features: a regional game-theoretic setup, and an endogenous treatment of technological innovation for energy conservation and decarbonization. A top-down inter-temporal Ramsey-type optimal growth model is hard linked with a representation of the energy sector described in a bottom-up fashion, hence the hybrid denomination. The regional and intertemporal dimensions of the model make it possible to differentiate and assess the optimal response to several climate and energy policies across regions and over time. The non-cooperative nature of international relationships is explicitly accounted for via an iterative algorithm which yields the open-loop Nash equilibrium between the simultaneous activity of a set of representative regions. Regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of fossil fuels and carbon permits, and technological R&D spillovers. R&D investments are directed towards either energy efficiency improvements or development of carbon-free breakthrough technologies. Such innovation cumulates over time and spills across countries in the form of knowledge stocks and flows.

The competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors, is described through a soft link with a land use and forestry model (GLOBIOM, Global Biosphere Management Model, see (Havlík et al., 2014)). A climate model (MAGICC) is used to compute climate variables from GHG emission levels and an air pollution model (FASST) is linked to compute air pollutant concentrations. While for this exercise WITCH is used for cost-effective mitigation analysis, the model supports climate feedback on the economy to determine the optimal adaptation strategy, accounting for both proactive and reactive adaptation expenditures.

WITCH-GLOBIOM represents the world in a set of a varying number of macro regions – for the present study, the eversion with 13 representative native regions has been used; for each, it generates the optimal mitigation strategy for the long-term (from 2005 to 2100) as a response to external constraints on emissions. A model description is available in (Bosetti et al., 2006b), and (Emmerling, Drouet, Reis, Bevione, Berger, Bosetti, Carrara, Cian, D'Aertrycke, et al., 2016), and a full documentation can be found at http://doc.witchmodel.org.

7 Differences in model behaviour

1. Electricity prices and demand (Figure S4 and Figure S5)
   Most models show monotonously increasing final energy demand for electricity, even with stringent climate targets. The exceptions are WITCH and

IMAGE. In these models, the introduction (2020 in Early action, 2030 in Delayed action scenario) of the stringent budget constraint leads to very high electricity price hikes (due to a carbon price) and a subsequent depression of demand for the first ten years.

In WITCH, this is due to the representation of competition of different technologies in the power sector via a production function with constant elasticity of substitution, which likely underestimates the amount of variable renewable energy that can be integrated into the power system with low integration costs (Pietzcker et al., 2017).

In IMAGE, the flat demand trajectory in the years subsequent to 2020 (in the early action scenario) occurs due to a combination of strong energy efficiency measures and low capacity addition. This is caused by the sudden and sharp increase of the carbon price. Energy efficiency measures are already favourable in the NDC scenario because of their short payback time, but face implementation barriers (also accounted for in this scenario). In the Early Action scenario, these barriers are loosened, as it is expected that that the short pay-back time becomes more attractive. Electricity price - the demand function uses the average generation cost as a proxy for determining the demand response. The high electricity price is the result of the coal-fired power plants that were already in the pipeline during the introduction of the carbon tax. In all other models, price increases are more moderate. The combined effect of increasing incomes and relative price competitiveness of other power supplying technologies compensate the higher prices from fossil sources.

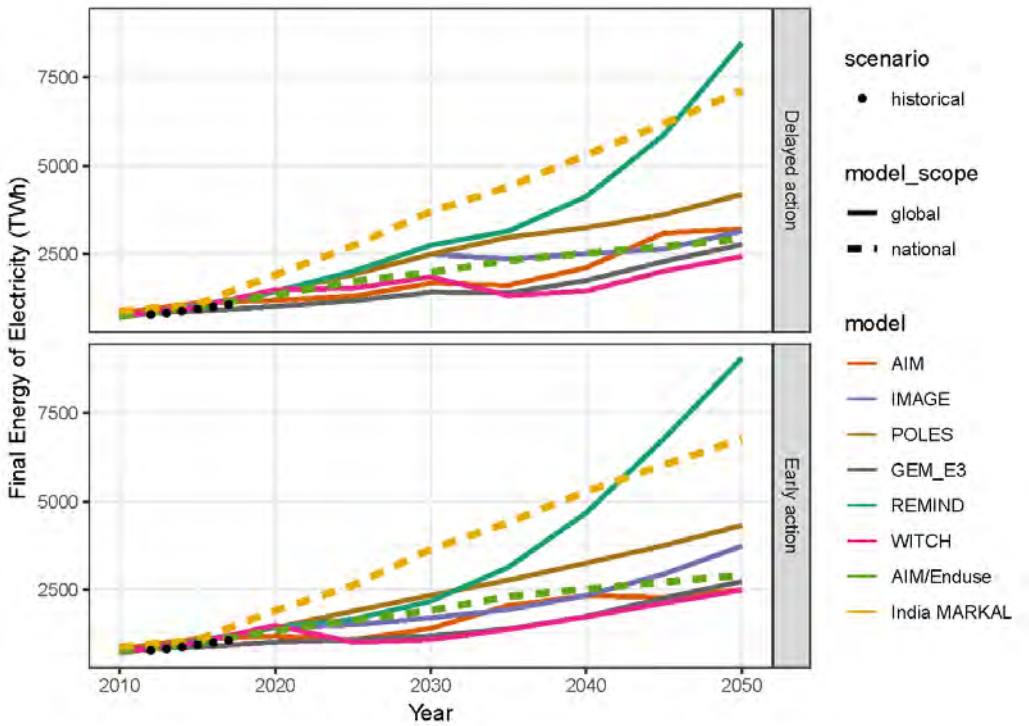

Figure S4 a), b) Final Energy of Electricity in EJ/yr, for the period 2010-2050, for the different national (dashed line) and global models (bold), for the two scenarios – Delayed and Early action.

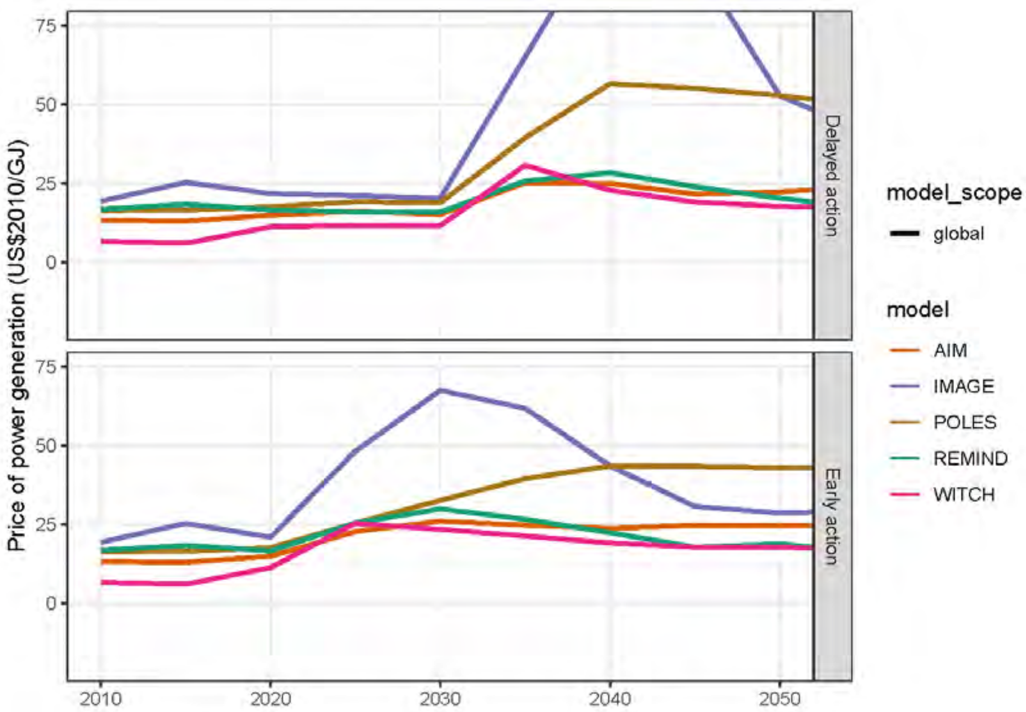

Figure S5 a), b) – Price of power generation (USD2010/GJ) for the Delayed and Early action scenarios from 2010-2050. Results are only for the global models (excluding GEM-E3)

2. Impact of stringent policy on renewable capacity additions

The model IMAGE shows higher absolute capacity of solar and wind in the delay scenario compared to the early scenario (Figure 5). In the latter, between 2020 and 2030 electricity prices skyrocket (Figure S5). These prices represent the average generation costs, i.e. the total system costs divided by the amount of electricity generated. The prices increase because of the introduction of a carbon price and the inability of the model to remove current coal capacity fast enough. As a result, the demand for electricity stagnates (Figure S4); the high prices lead to efficiency improvements and substitution towards other energy carriers. Subsequently, demand for additional capacity, between 2025 and 2030, is small leading again to the lower installation numbers for wind and solar. After 2030, the electricity price reduces again. With the expensive fossil capacity now retired, new low-carbon sources are installed.
The other models have a more direct representation of demand elasticity, where marginal prices of additional generation determine the electricity price, so that all technologies that can produce at generation costs lower than the demand price will be expanded and an equilibrium between supply and demand prices is reached. In some of those models, there are also constraints on the speed of coal-power phase-out (so even though coal generation is expensive, it continues to exist), which implicitly represents a subsidy to these generators (either through direct payments or exemptions from carbon tax or permit requirements).

3. Gas-based power generation and CCS availability in AIM/Enduse

   The model AIM/Enduse shows significant expansion of gas-based electricity in both early and delay action scenarios till 2030 (Figure 3). This is based on the potential of large-scale discovery and exploitation of shale-gas in India (personal communication). Furthermore, AIM/Enduse also projects significant production of power from CCS technologies (Figure 5). The costs and availability of storage sites of CCS, as well as the policy landscape on CCS are from various reports and papers (A. Garg et al., 2017; Press Information Bureau, 2015, 2017)

4. Total coal power generation in GEM-E3

   GEM-E3 model is not included in the range of results of global models on power generation. GEM-E3 model results show discrepancies in power generation in the base year (2010) due to the following: i) the GEM-E3 model is calibrated to year 2011 in line with the GTAP economic database, ii) electricity production and other energy variables in GEM-E3 are calibrated to the IEA energy balances, however total electricity production is reported as production by power plants and auto producers, excluding losses (particularly high in India) and energy industry own use. Overall, deviations in GEM-E3 are not fuel-specific as the power mix in the base year is consistent with data and within the range of other global models, while differences are identified in total power production volumes.

8 Key Socio-economic indicators

Key socio-economic indicators often differ across models and represent differing assumptions and understanding of the ongoing social and economic transformation of the country, and their evolution into the future (Dubash et al., 2018). These include population, GDP and final energy demand.

The population increase in the models till 2050 is robust (Figure S6). However, the variations in GDP are significant and divide the eight models into roughly two groups – models with GDP in the range of USD 7.5 -10 trillion and those in the range of USD 13-16 trillion in 2050 (Figure S7). The Final Energy needed to fuel this growth is 27-94 EJ/yr in 2050, thus also showing a large variation (Figure S8).

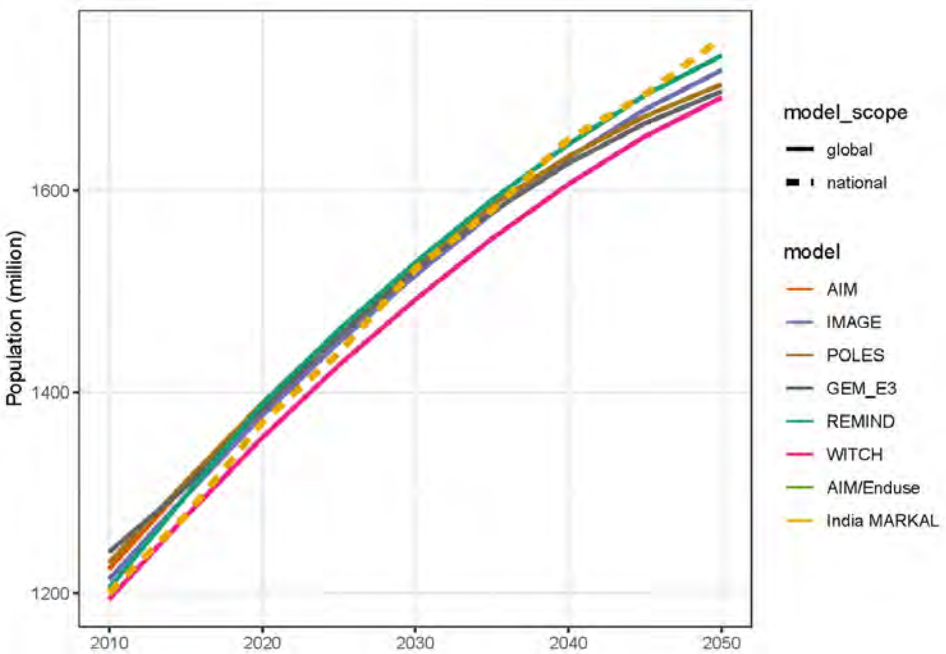

Figure S6 Population (million) in global and national models during the period 2010-2050

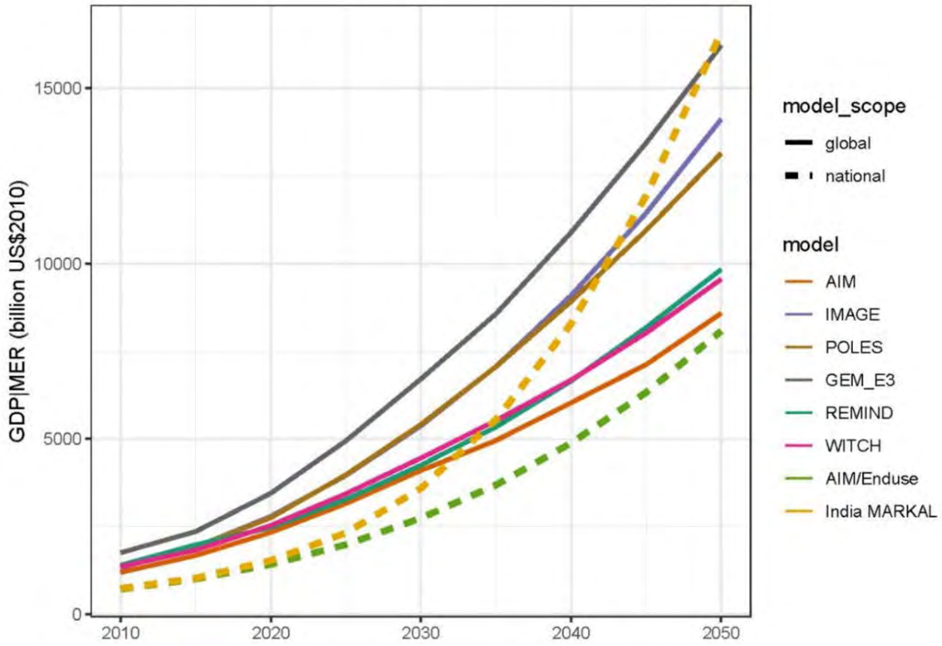

Figure S7 GDP in Market Exchange Rate (USD billion 2010) for different global and national models from 2010 to 2050.

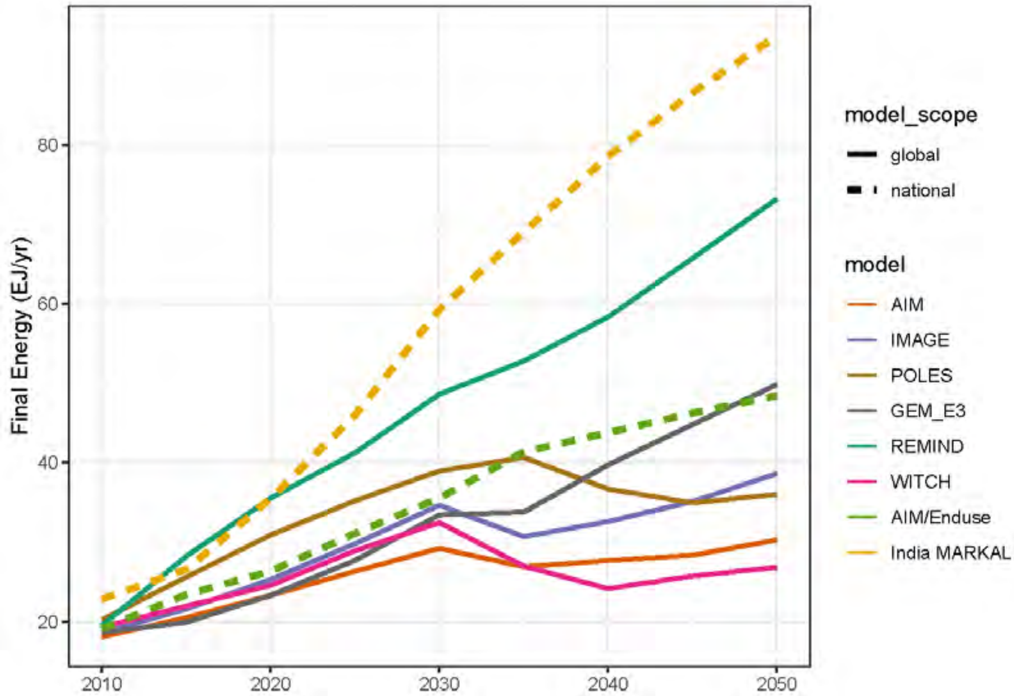

Figure S8 Final Energy demand (EJ/yr) for the delayed action scenario for the different national and global models from 2010 to 2050.

9 Additional Figures

Carbon Price

a) b)

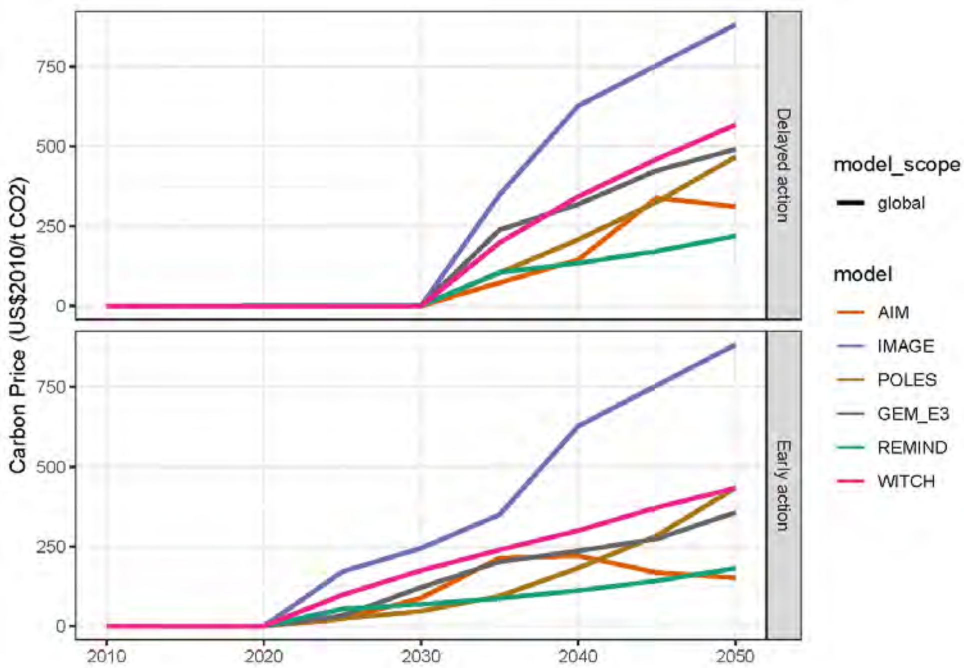

Figure S9 a) b) Carbon Price (in US$2010 per ton of CO2) for the two scenarios- Delayed and Early action. The coloured lines represent different global models

Power generation from coal in Early action

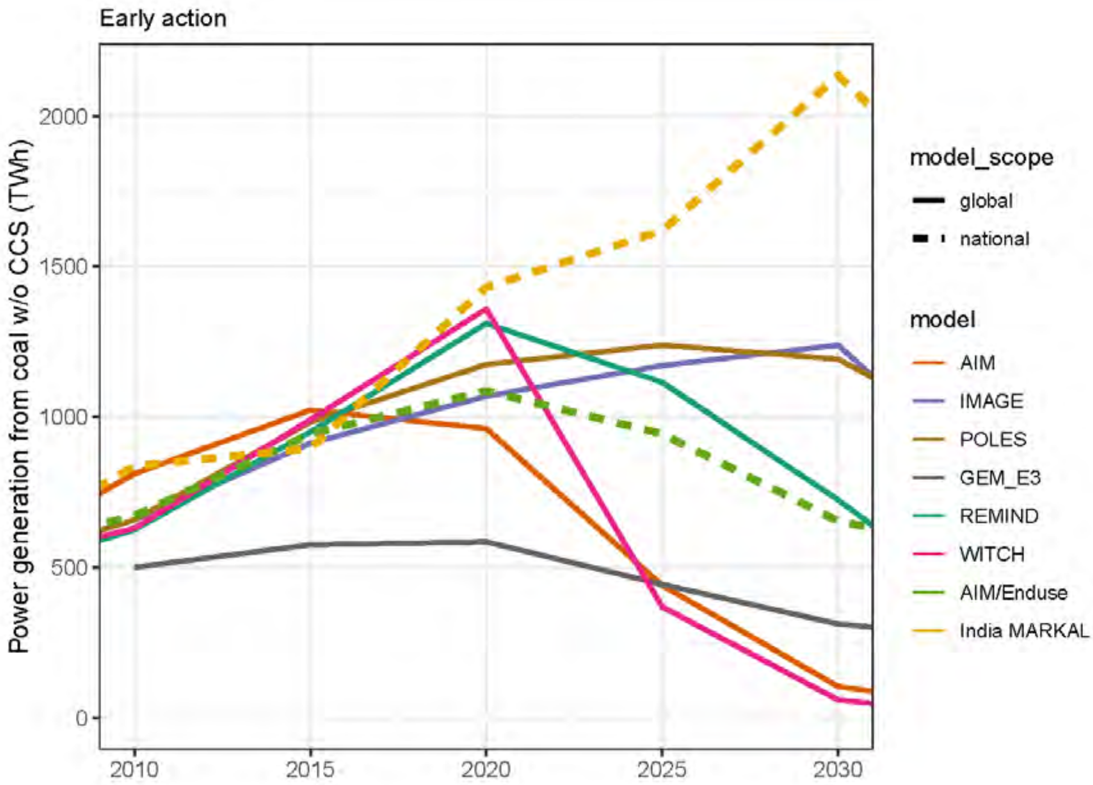

Figure S10: Power generation from coal without CCS in early action scenario (2010-2030). The different colors represent the different models, national models are dashed.

Emissions from energy and electricity sector

a) b) c) d)

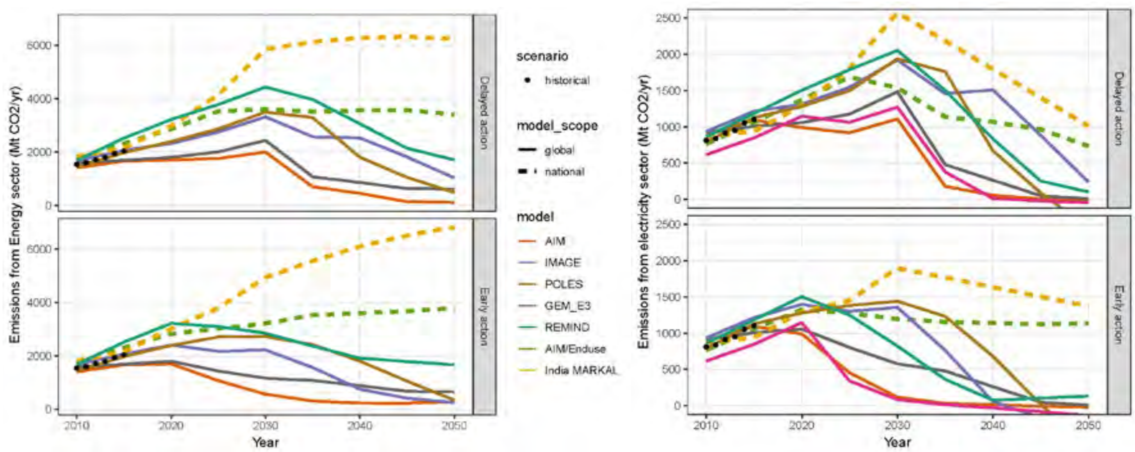

Figure S11 a), b) Emissions from the energy sector (in Mt CO2/yr) , c), d) – emissions from the electricity sector, for the different national and global models for the scenarios – early and delayed action between the period 2010 and 2050. The black dots represent historical values from CDIAC (Carbon Dioxide Information Analysis Centre- https://cdiac.ess-dive.lbl.gov/).

Cumulative emissions

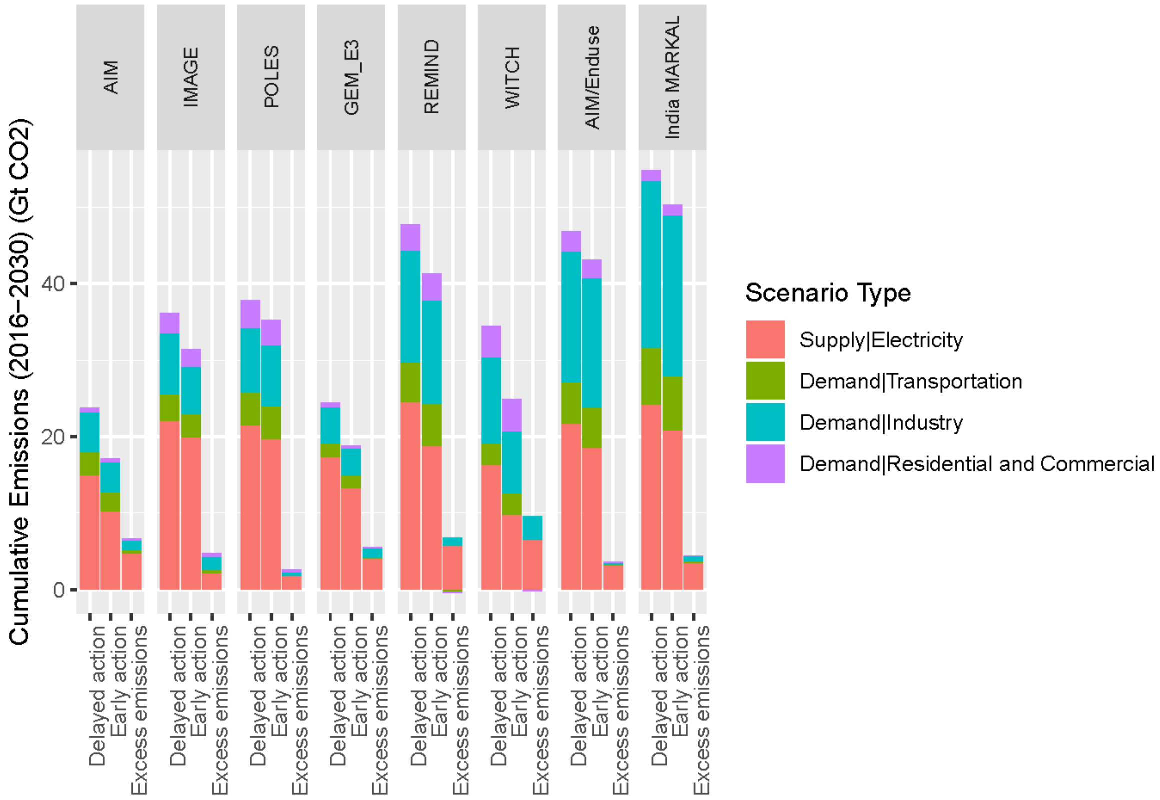

Figure S12 Cumulative emissions categorised according to source - Electricity (red), Transportation (green), Industry (turquoise) and Residential and Commercial (purple), for the different models, for the two scenarios – Early and Delayed action, and the excess emissions due to delayed action.

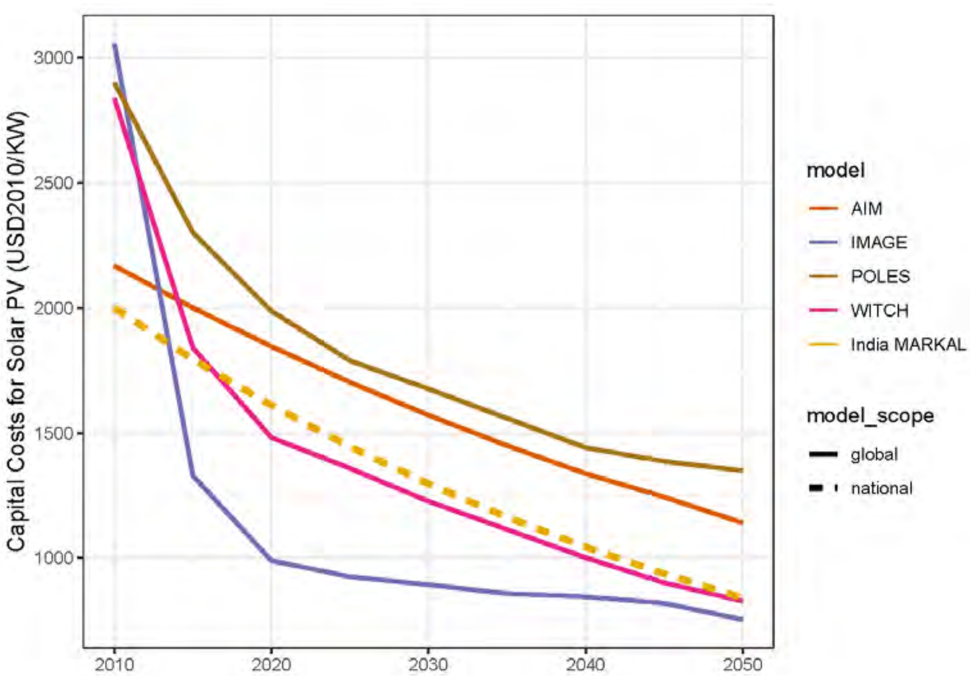

Figure S13 Capital costs for Solar PV (in USD2010/KW) across models. Notre that not all models report this variable.

10 Stranded Capacity

The "stranding of coal power plants" can be understood as the foregone potential of a power plant (to be produce electricity because of a climate policy (carbon price), when compared with a counterfactual. In this study, the counterfactual assumes that all coal power plants run at ~60 % capacity factor and retire after 40 years. Thus, one way of calculating the foregone potential is finding the difference between the counterfactual generation and generation in a policy scenario. Another way to show this is through stranded capacity. The policy scenario shows a much lower electricity generation compared to the counterfactual. As the capacity factor of the power plant cannot be changed (assumption), it implies that some plants need to be closed. Therefore, plants which would have lived until their lifetime must be prematurely closed. This is termed as stranded capacity. The advantage of the second approach is that it allows us to visualise early retirement/premature shutdown and the age of the power plants when forced for a shutdown. The latter gives us an indicator of the scale of decarbonisation required and the disruption it would cause, because the closure of younger plants is more expensive than older plants which have already extracted a larger share of their investments.

Calculation of Stranded Capacity and age of stranded capacity

1. From secondary energy to capacity:
    a. The calculation of stranded assets requires the projection of coal capacity (in GW) in the models. However, in most models, the variable "Secondary Energy|Electricity|Coal" is often calibrated against historical data on power generation, while the variable "Capacity|Electricity|Coal" is not calibrated and hence the former is a more reliable indicator of of electricity derived from coal combustion.
    b. The Secondary Energy|Electricity|Coal for all years after 2020 is normalised to the 2020 value.
    c. Thus, assuming the 2020 value to be 4.22 EJ[6], all future power generation is calculated by multiplying this value with the normalised factor from the previous step.

[6] Data from 2018. Sum of 986591 GWh from Coal/lignite (utilities) and 147035.84 GWh from "steam" captive (non-utility/captive) plants (Central Electricity Authority, 2018b). All "steam-based plants are assumed to be running on coal/lignite. To this a generation of 40313 GWh based on a capacity addition of 7.8 GW of coal power in 2019 is added taking the overall sum to 1174 GWh.

   d. The Secondary Energy|Electricity|Coal from the previous step is converted to coal capacity using a capacity factor of 0.59 - the current average capacity factor of coal plants in India (Central Electricity Authority, 2018a)

2. Age structure of coal capacity:
   a. The age of all operating coal power plants in India until end of 2018 is used (Coal Swarm, 2019) to calculate the capacity (GW) per age.
   b. For the early action scenario, the age structure of the operating plants is calculated in 2020, assuming no capacity build-up during 2020, capacity addition of 7.8 GW during 2019 (IEA Clean Coal Centre, 2019), and all plants until 2018 getting older by two years. Thus, for every model, the 2020 capacity is the same and has the same age structure. A separate file called "age structure.xlsx" has been provided for point a and b.
   c. Not all models in **early action scenario** stop building coal after 2020. IMAGE and India MARKAL achieve their peak in 2030 and POLES in 2025. For these models, capacity is added, starting from 2020 till their peaking year. See Figure S13a. All plants older than 40 years are assumed to be retired and thus excluded.
   d. For the **delayed action scenario**, the peak capacity is achieved in 2030 in all models. The plants operating in 2020 are assumed to be 10 years older in 2030. All plants older than 40 years are assumed to be retired and thus excluded.
   e. The remaining capacity (model result in 2030 – operating plants from 2020 in 2030) is distributed equally amongst the preceding years (2020-2030). To illustrate this point, see Table S6.

Model name	Total coal capacity in 2020 (GW) **A**	Coal capacity older than 40 years and retired by 2030 (GW) **B**	Coal capacity in 2030 in delay scenario (GW)[7] **C**	Coal capacity added during 2020-2030 (GW) **C-(A-B)**	Coal capacity added each year during 2020-2030 in delay scenario (GW)
REMIND	227	22.3	350.4	145.7	14.6
AIM	227	22.3	273.3	68.6	6.9
IMAGE	227	22.3	400.4	195.7	19.6
WITCH	227	22.3	230.3	25.6	2.6
GEM-E3	227	22.3	336.7	132	13.2
India MARKAL	227	22.3	437.9	233.2	23.3
POLES	227	22.3	339.5	134.8	13.5

Table S6 Table showing the linear interpolation of added coal capacity during 2020-2030 in the delay scenario.

Stranded Capacity:

f. The absolute stranded capacity is the difference between the line following the natural retirement of plants (following the top of the yellow line in Figure S14a and Figure S14b) and the modelling result of a mitigation scenario (black line).
g. The average of the stranded capacity (GW/yr) for Early and Delayed scenarios over time (2020-2050 for Early action and 2030-2050 for Delayed action), and by age-group is shown in Table S7 and Table S8.

Absolute stranded capacities for the two scenarios (early and delayed), for the different models, at specific time periods is shown in Figure S14.

[7] As calculated from 1d

a)

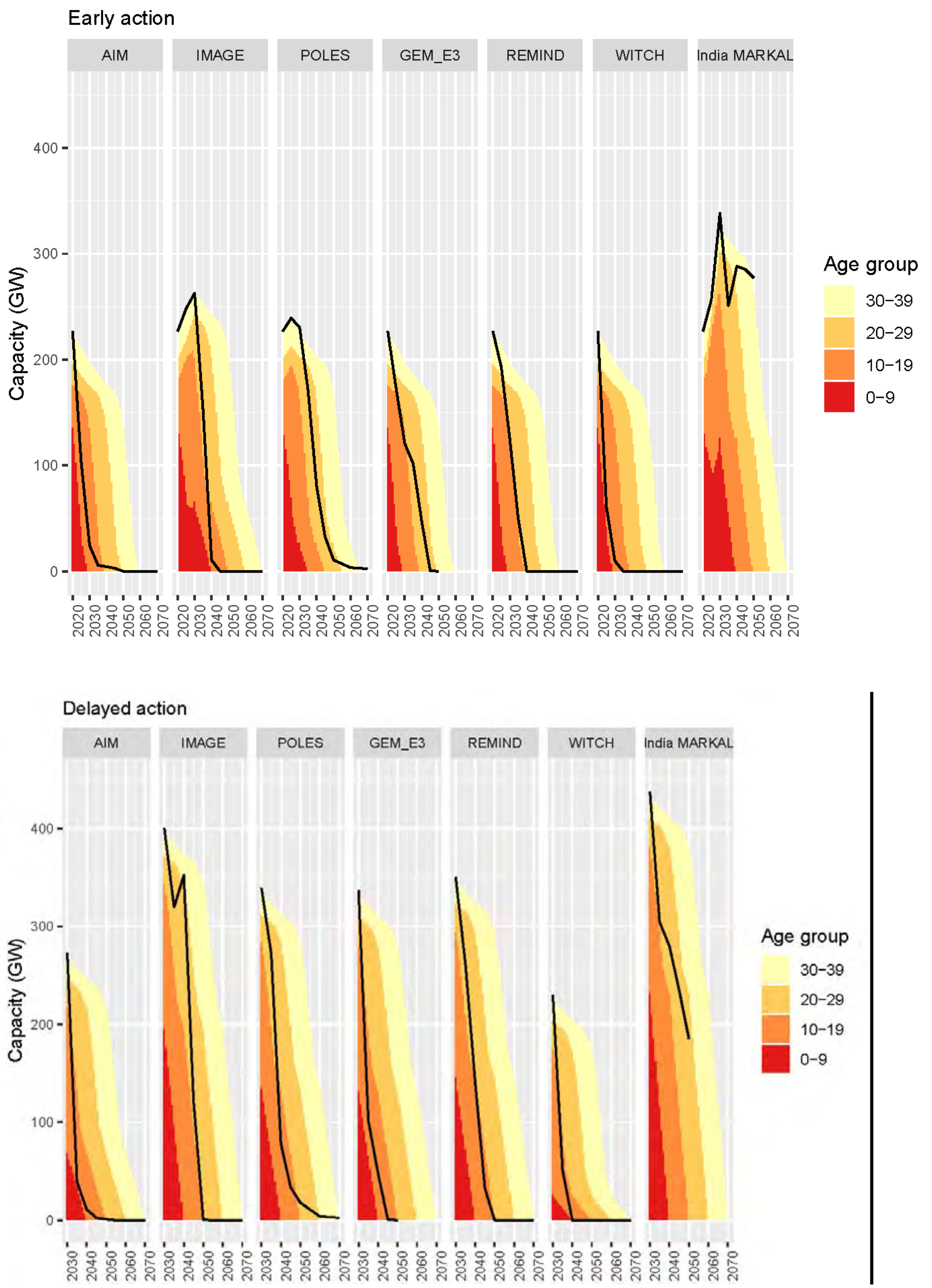

Figure S14 Coal capacity development, assuming natural retirement and colored according to age-group, black lines are model scenario outputs for a) Early action and b) Delayed action

Model	Average stranded capacity (GW)			
	Early action		Delayed action	
	2020-2050[8]	2020-2060[9]	2030-2050	2030-2070
AIM	147	123	205	134
GEM_E3	97	-	237	-
IMAGE	119	120	134	155
India MARKAL	14	-	133	-
POLES	75	83	179	150
REMIND	109	14	179	158
WITCH	159	138	167	107

Table S7 Average stranded capacity in early and delayed action scenarios for the different models and the median across all models. In order to compare stranded capacity across the same duration of 40 years, another time period has been shown (2021-2060 and 2031-2070) but this excludes GEM_E3 and India MARKAL which run only till 2050.

Age-group at the time of stranding (years)	Median stranded capacity (GW)			
	Early action		Delayed action	
	2020-2050	2020-2060	2030-2050	2030-2070
0-10	NA	NA	NA	NA
11-20	30	55	34	33
21-30	65	61	101	84
31-40	52	50	64	66

Table S8 Median of stranded capacity differentiated over age-group. In order to compare stranded capacity across the same duration of 40 years, another time period has been shown shown (2021-2060 and 2031-2070) but this excludes GEM_E3 and India MARKAL which run only till 2050

[8] Includes all models

[9] Includes all models except India MARKAL and GEM_E3

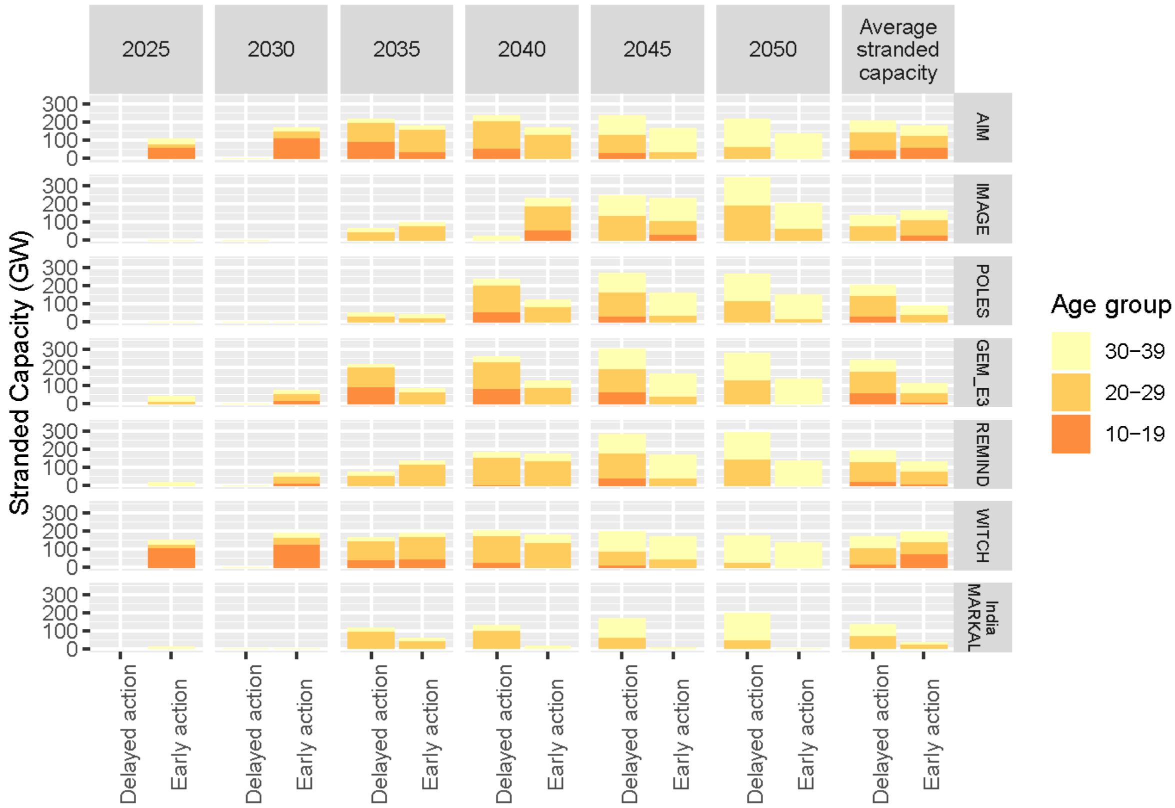

Figure S15 Stranded capacity (GW) for the two scenarios - Delayed and Early, for the different models, at specific intervals in time. Average stranded capacity is the average of the stranded capacity across 2025-2050 similar to Table S7. Colors represent age-group.

11 Alternatives to coal: Nuclear and Hydropower

a) b)

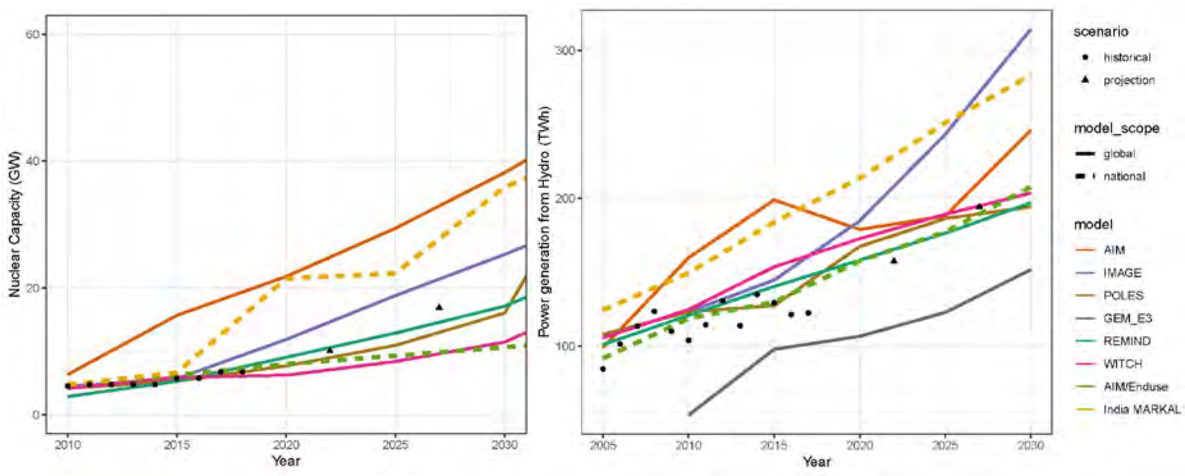

Figure S156(a-b) Projections of Nuclear Capacity (GW) and Power generation from Hydropower (TWh) for the different models under delayed action. Black dots are historical numbers and black triangles are projections, both from the CEA.

The projections of nuclear capacity till 2030 divide the models into two groups – those with projections higher and lower than CEA (Figure S16a). For those models, with projections higher than CEA and assumed to be optimistic about near-term nuclear growth, several factors make this scenario unlikely. First, unlike other sources of generation (like coal, gas, and RE) which have been liberalised, nuclear-based generation in India is still solely controlled by the central government (World Nuclear Association, 2019), thus preventing rapid build-up as witnessed in coal power plants. Second, India was excluded from trade in nuclear plants and materials until 2009, as it was a non-signatory to the nuclear non-proliferation treaty. Since 2009, although India is allowed to carry out nuclear trade with the rest of the world, a significant disagreement between India's civil liability law and international conventions has limited foreign technology provision (World Nuclear Association, 2019). Third, public opposition has grown (Srivastava, 2011) since the Fukushima Nuclear disaster and under-construction plants are facing safety concerns and funding constraints (Ebinger, 2016). The factors mentioned above have led India's largely indigenous nuclear program to face extra-ordinary planning and construction delays and eventually cost over-runs in the past; the average construction times of nuclear plants in India are twice the world average[10].

As of 2019, India has 6780 MW of nuclear capacity, with another 6700 MW under construction. Although India mentioned an aspirational target of 63 GW by 2032 in

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[10] Own calculation. Data from (*World Nuclear Performance Report*, 2018) and Wikipedia pages of various nuclear plants in India, e.g., https://en.wikipedia.org/wiki/Kaiga_Atomic_Power_Station

its NDC (India's NDC, 2015), the estimated construction would be likely lower (around 23 GW in 2031) (Government of India, Department of Atomic Energy, 2018) , which is the target taken up by the CEA.

Thus, in view of the barriers mentioned above, the projections close or lower than those of CEA might be more plausible than the optimistic ones.

The share of hydropower in India's electricity generation has gradually decreased over time (Standing Committee on Energy, 2019). Hydropower projects in India, like many projects globally, face severe delays (problems of land acquisition and litigation) and average construction period is eight years[11] (Standing Committee on Energy, 2019). To increase the growth of hydropower in India, the Ministry of Power reclassified large-scale hydropower (>25 MW) as renewable energy, in the process providing it with subsidies and other economic benefits (Dutta, 2019). However, this would still not ease other environmental and social problems accompanying hydropower, especially in the fragile Himalayan ecosystem.

Most models project nominal growth of hydropower in the near-term, broadly in line with CEA projections.

12 Drivers of current and future stressed assets in coal power generation

In 2018, 34 coal-fired power plants with a combined capacity of 40 GW[12] (current coal capacity is 222 GW) were identified as "stressed" (Standing Committee on Energy, 2018). There has been some debate on the causes of these stressed assets, although it is clear is that there is no one single cause. The 12th plan (2012-2017) witnessed a record capacity addition (mainly coal) and coupled with a lower than expected growth in power demand, resulted in falling plant load factors (Srikanth, 2017; Standing Committee on Energy, 2018). This affects the revenues of power generators. Although the demand is projected to increase manyfold as transmission grid infrastructure picks up , the current and projected over-capacity (from RE targets and coal plants under construction), would still lead to lowering PLFs (Central Electricity Authority, 2018a). This, coupled with the increased burden through new environmental norms, (adding operational and capital expenditure (Central Electricity Authority, 2016), would increase the likelihood of more stressed and stranded assets, in spite of the retiring of old inefficient plants (Central Electricity Authority, 2018a). Other factors contributing to stressed assets, include

[11] averaged from capacity added in 2012-2017

[12] Includes commissioned capacity of 24.4 GW and under-construction capacity of 15.7 GW. Subsequent reports estimated a higher number of 75 GW(Trivedi & Singh, 2018); the difference arising partly due to different definitions of a stressed asset.

the absence of coal linkages and power purchase agreements (Standing Committee on Energy, 2018; Worrall et al., 2019), while some cite the growing competitiveness of solar and wind (Gray, 2018).

13 Air-pollution and Coal power

The impact of air pollution on human health has been a source of intense discussion in last decade in India – both due to its visible and physiological impacts and publication of studies quantifying premature mortality and loss to GDP (Balakrishnan et al., 2019; World Bank, 2016). To reduce the concentration of pollutants, particularly PM2.5, a number of policies and regulations have been introduced in different sectors.

Of the total estimated annual anthropogenic emissions in India, power generation accounts for approximately 10% of PM2.5, 30% of NOx, and 50% of SO2 (For 2015, estimated from Fig. 6 Purohit et al., 2019). In 2015, the Ministry of Environment, Forest, and Climate Change (MoEFCC) set standards limiting the concentration of four pollutants (Mercury, SO2, NOx, and PM (Particulate Matter)) emitting from coal power plants. These standards differ depending on the year of installation and size of the plants, with newer and bigger plants having the strictest regulations (Central Electricity Authority, 2018a; *The Gazette of India*, 2015). Implementing these standards will require installing control instruments, adding to the variable and fixed costs and thereby increasing the cost of electricity generation (V. Garg, 2019). Moreover, some plants (16 GW or 3 % of current installed capacity) will need to be retired as they will be unable to meet these new regulations, owing to space constraints (Central Electricity Authority, 2016). However, these regulations would significantly decrease the absolute and share contribution of power plants to total annual anthropogenic emissions (Purohit et al., 2019). Thus, at the outset, the stricter regulations would have minimal effect on early plant closure.

However, a few caveats and political economy considerations remain. Considering the leveraging of electricity for political gains in India, distribution companies, already under severe debt, might be unwilling to accept higher prices without the guarantee of selling it at higher rates (V. Garg, 2019). Considering the plummeting PLF of plants (projected to decrease further (Central Electricity Authority, 2018a) under increasing shares of VRE), and the significant mark-up of abatement equipment (9-20%; Vibhuti Garg, 2019), an inability to recover these costs could lead to premature retirement. These effects might be exacerbated for already stressed plants and for plants in and around major cities like Delhi, which might be come under further regulations - such as forced shutdown during periods of increased pollution, permanent shutdown (Express News Service, 2015) or running them at lower PLFs (V. Garg, 2019).

14 Relevant limitations of Integrated Assessment Models

Challenges of modelling power system with high VRE shares

None of the models used in the study do hourly modelling. However, as part of the ADVANCE project, several of the (mostly) global models used in this study improved their parametrisations of VRE (solar and wind) integration by comparing results with REMIX - an energy system model with hourly resolution (Pietzcker et al., 2017). Thus, each model introduced a suite of approaches to better represent the power system dynamics. These were broadly classified into five themes – investment dynamics, power system operation, temporal matching of VRE and demand, Storage and Grid requirements. However, all of the presented approaches have their limitations and none of the models covered all aspects to the best extent possible (Pietzcker et al., 2017). Moreover, the same models in this study may not have preserved all the features used in the ADVANCE study.

The considerations to capacity factor and storage for each model are given below:

Model	Modelling of capacity factor in coal power plants	Modelling of energy storage in power system
AIM	Capacity factors are fixed (region-, technology- and time specific) parameters in AIM. Capital of technologies are dealt with already built and newly installed for each year. Early retirement can happen based on the logit-sharing equation.	The storage requirement is determined by poly-nominal function of renewable energy share in the power generation (Dai et al., 2017)
GEM_E3	GEM-E3 hybrid CGE model features a soft-link to more detailed energy system models. For this analysis, the soft-link option has been utilized. This soft-link features fixed Capacity Factors (differentiated by region, technology and year) and allows for early retirement of investments.	No energy storage capacity in power system
IMAGE	Capacity factors for coal fired power plants are variable and depend on the demand from the different sectors captured in the regional (residual) load duration curve, and the variable costs that determine the merit order. The maximum load factor is calculated on the basis of assumptions on the outage rate (5%) and the forced outage rate (5%). See (de Boer & van Vuuren, 2017) for more details.	Short-term storage is included. Storage capacities increase with renewable shares. Exogenous storage investments are based on renewable shares (based on DIMES model) and have effect on curtailment and capacity (See (Ueckerdt et al., 2017)

India MARKAL	Capacity factors are fixed by technology, but based on demand and supply, the model would indicate levels of unutilised capacity utilization, if there are stranded capacities over time.	Implicitly determined with increasing share of renewables in the power mix.
POLES	Capacity factors vary by region, technology and year according to the power demand and supply balance, detailed in winter and summer typical days. Vintages of technologies are explicitly tracked with technology specific lifetimes. Early retirement is not possible but retrofit of plants to CCS is allowed once the technology is developed	This version of the model only includes seasonal hydro storage and demand side response through hydrogen production.
REMIND	Capacity factors are fixed (region-, technology- and time specific) parameters in REMIND. Vintages of technologies are explicitly tracked with technology specific lifetimes. Early retirement is possible (see vm_capEarlyReti in the code[13]) with a constraint on the ramp-up of the retired fraction of capacity stocks.	An equation in the model (see q32_shStor in the code[14]) determines storage requirements that increase with increasing shares of variable renewables.
WITCH	Capacity factors are fixed (region-, technology- and time specific) parameters	The limitation to VRE penetration into the electrical grid is modelled

[13] https://github.com/remindmodel/remind/blob/develop/core/equations.gms
[14] https://github.com/remindmodel/remind/blob/develop/modules/32_power/IntC/equations.gms

	in WITCH. Early retirement of installed capacity is possible.	through two explicit constraints, a constraint on the flexibility of the power generation fleet and a constraint on the installed capacity of the power generation fleet. The latter is becoming more important with increasing penetration of intermittent renewables. Moreover, electricity storage is modelled through an investment in a generic storage technology.
AIM/Enduse	Capacity factors are fixed (region-, technology- and time specific) parameters. Vintages of technologies are explicitly tracked with technology specific lifetimes. Early retirement is captured in two ways: a) with a constraint on the ramp-up of the retired fraction of capacity stocks and b) selection by model based on combination of investment, technology price and/or fuel price constraint in future years	The limitation to VRE penetration into the electrical grid is modelled through: a) a constraint on the installed capacity of renewables and b) investment in the storage technology.

Table S9 Modelling of capacity factor in coal power plants and energy storage systems in power systems for different models.

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Chapter 3

Climate change accelerates structural changes in the employment sector[*]

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Climate policy accelerates structural changes in energy employment

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ABSTRACT

The employment implications of decarbonizing the energy sector have received far less attention than the technology dimension of the transition, although being of critical importance to policymakers. In this work, we adapt a methodology based on employment factors to project future changes in quantity and composition of direct energy supply jobs for two scenarios - (1) relatively weak emissions reductions as pledged in the nationally determined contributions (NDC) and (2) stringent reductions compatible with the 1.5 °C target. We find that in the near-term the 1.5°C-compatible scenario results in a net increase in jobs through gains in solar and wind jobs in construction, installation, and manufacturing, despite significant losses in coal fuel supply; eventually leading to a peak in total direct energy jobs in 2025. In the long run, improvements in labour productivity lead to a decrease of total direct energy employment compared to today, however, total jobs are still higher in a 1.5 °C than in an NDC scenario. Operation and maintenance jobs dominate future jobs, replacing fuel supply jobs. The results point to the need for active policies aimed at retraining, both inside and outside the renewable energy sector, to complement climate policies within the concept of a "just transition".

1. Introduction

Reduction of emissions to reach the goals of the Paris Agreement will require a drastic energy transition– not only replacing fossil fuels by renewables for power generation, but higher end-use electrification, adoption of other low-carbon fuels, greater energy efficiency, and behavioural change (Dubois et al., 2019; Luderer et al., 2018; Weber, 2015).

The employment implications of decarbonizing the global energy sector system are of critical importance for the political salience of global mitigation pathways towards the goals of the Paris Agreement. Employment in the energy sector represents a tiny fraction (~1.2%) of total global employment. In 2019, against a total world employment of around 3.3 billion (15+ age) (ILO, 2020) there were only 40 million total world energy jobs (including production, distribution, and transportation) (IEA, 2020). Despite the insignificant overall share, energy sector jobs, especially on the supply side are directly and visibly linked to energy policy, are a source of indirect job creation, and important revenue for states and sub-regions. Thus, their consideration is critical to the speed and direction of energy transition.

An energy transition will lead to a change in the number, structure, and required skill of jobs in the energy sector. To be sure, such a 'conscious', policy-induced transition will be superimposed to an autonomous long-term trend towards more service-based economies and increasing endogenous labour productivity (often accompanied by shift in factors of production from labour to capital). Whatever the type of transition, two things are clear – i) job creation and employment will continue to be a major political force affecting political decisions at all administrative levels, and ii) unlike a "natural transition", there will be higher resistance to a "conscious transition", especially because the long-history of incumbent technologies has resulted in strong political affiliations and lobbying power of relevant stakeholders, both regionally and nationally (Caldecott et al., 2016; Spencer et al., 2018). In some cases, such as coal, a which have a long history in certain regions, the loss would not only be that of employment but whole cultures – festivals, language etc.

The emerging field of "just transition", defined as "a process by which economies that progress towards a green economy also strengthen each of the four pillars of decent work for all (i.e. social dialogue, social protection, rights at work and employment)" (ILO, 2018) has partly arisen to ease the opposition from people/groups, whose jobs which will be lost or at risk of being lost due to an energy

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transition and to dilute the climate-specific focus of energy policies to include broader societal goals as put down in the Sustainable Development Goals SDGs, thereby increasing political support (McCauley and Heffron, 2018).

To contribute to both the ongoing effort on societal implications of energy transitions and political feasibility of scenarios (in the context of employment) requires first and foremost, a technology-specific quantification of energy sector jobs under alternative policy pathways. Thus, the first objective of the paper is to bring forth a transparent and in-depth methodology of estimating employment, including identifying its most important drivers. The second objective is to find differences in near-term and long-term structure of (global) jobs in the energy supply sector. Lastly, using this information, we seek to identify if employment transitions in the near-term could hinder decarbonisation.

The current study provides a method to account for employment effects of global climate policy scenarios, which although widely used in international scientific and policy communities (e.g., IPCC), hardly provide employment impacts. Previous studies using this method, include energy models (Dominish et al., 2019; Ram et al., 2019, 2022) and global integrated assessment models (IAM) (Pai et al., 2021). We go beyond these studies by discussing in detail the uncertain but crucial determinants for energy employment.

2. Methods

2.1. Overview of methodologies for estimating energy employment

Approaches to measure employment effects from renewable deployment or energy policies can broadly be broken down into two types – i) those using input–output (IO) or computable general equilibrium models (CGE) of the economy, and ii) those relying on analytical approaches (Kammen et al., 2004). The former includes flow of goods and services between different sectors of the economy, i.e., everything produced either serves as an input to the next level of production or an end-use purpose (IRENA, 2014). This allows finding the macro-economic impacts, including employment, of various energy and climate policies (Lambert and Silva, 2012). However, their coarse sectoral coverage prevents detailed breakdown of jobs by technology and/or fuel (for studies using the GEM-E3 CGE see, for e.g., Vandyck et al., 2016; Vrontisi et al., 2020).

The second approach and more relevant for this paper involves calculation of job intensities or employment factors (EF), defined as the number of jobs resulting from a unit investment or unit production of a physical commodity. When combined with energy transformation pathways they yield gross employment (only direct jobs) in that sector, although multipliers have been used to extend the scope of the approach to include indirect jobs (IRENA, 2014). A schematic of the employment factor approach is shown in Fig. 1. Direct jobs in the energy supply sector are broken down into stages or activities commonly associated with the supply chain or life cycle of a fuel/technology – manufacturing, construction and installation (C & I), operation and maintenance (O & M), fuel supply or production. Each activity and technology require a separate employment factor and when estimating jobs globally, also country-specific factors. Since manufacturing and C & I jobs are only created during the capacity addition, they are multiplied to the added capacity, O & M to the existing capacity, and fuel supply factors to the fuel production. The distinction of jobs in the value chain also helps to distinguish between the temporal (short-term manufacturing and C & I jobs), spatial (export-oriented manufacturing jobs vs. regional C & I and O & M jobs), and to some extent worker-skills characteristic of each technology.

2.1.1. Estimation of employment factors

An important pre-requisite for the calculation of jobs in this study is the employment factor (EF). EFs have been reported in literature either through I/O models, industry surveys, or back-calculation based on employment and capacity figures in a particular year (Cameron and van der Zwaan, 2015). Several studies have aggregated and analysed these EFs, providing important insights – i) Renewables EFs are reported more often than conventional technologies (Cameron and van der Zwaan, 2015; IRENA, 2014; Lambert and Silva, 2012), ii) Most studies are for/from OECD countries (Cameron and van der Zwaan, 2015; Rutovitz et al., 2015), iii) EFs for RE technologies are much higher than conventional technologies (measured in MW or MWh) (del Río and Burguillo, 2008), and solar PV C & I + manufacturing EFs are higher than corresponding wind EFs (Cameron and van der Zwaan, 2015), iv) Large variation exists in EFs for similar technologies (Breitschopf et al., 2012; Cameron and van der Zwaan, 2015).The large variation in turn exists because of unclear boundaries between-direct and indirect jobs and the various activities in the supply chain; local and export/import

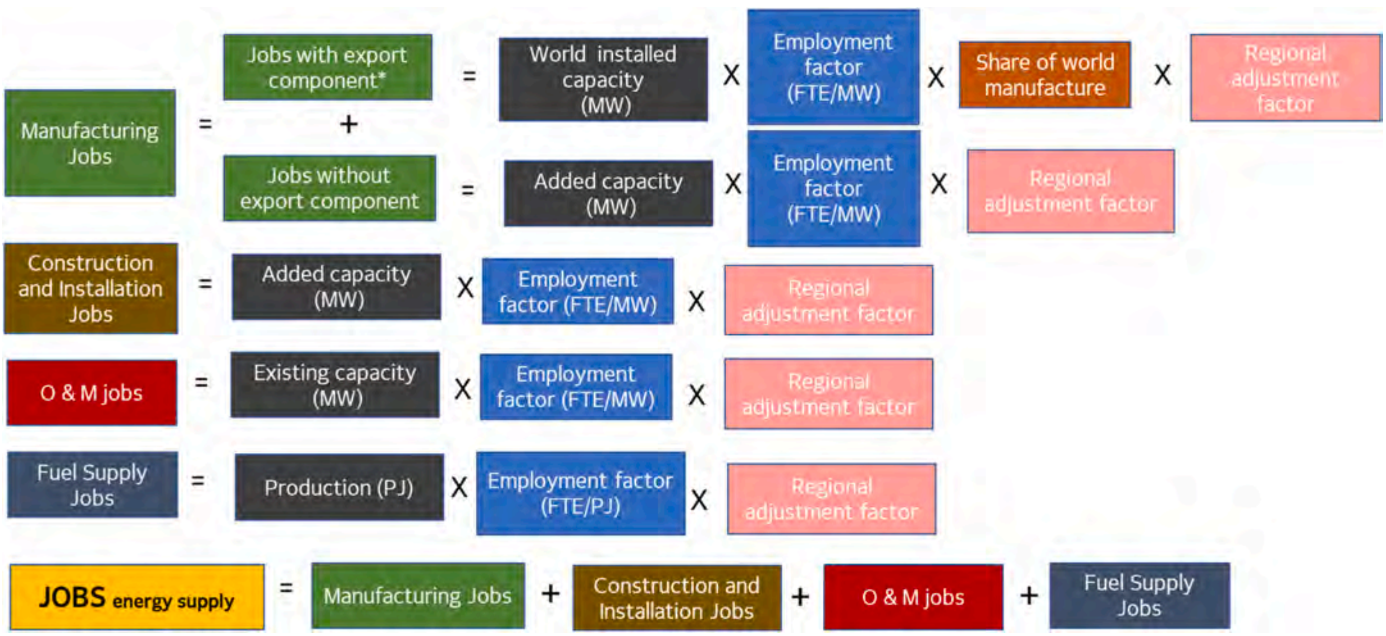

Fig. 1. Schematic explaining how direct energy supply jobs are calculated (Based on (Rutovitz et al., 2015, 2020).

component of jobs; specific country-contexts; and methodology (for e.g., not considering or reporting effects of economies of scale) (Cameron and van der Zwaan, 2015; IRENA, 2014). (Llera et al., 2013) further note that even with a consistent methodology for data collection, differences could still arise from maturity of the industry or availability of skilled workers.

2.1.2. Estimation of jobs using the EF approach

The EF approach has been used by many studies to calculate existing or future jobs in the energy sector, although most of them have been limited to regional or sub-regional scales and included only renewable technologies (Kammen et al., 2004; Stavropoulos and Burger, 2020). On the other hand, Rutovitz et al. have used the EF approach to calculate regionally differentiated global energy supply job estimates, divided by technology and type (Rutovitz et al., 2015; Rutovitz and Atherton, 2009; Rutovitz and Harris, 2012). Their methodological updates, published every three years, have updated the employment factors (as more data is discovered and/or made published) and expanded sectoral scope of jobs, e.g., from heat supply. Additions have also been made by (Ram et al., 2019, 2022) notably the inclusion of decommissioning, storage-battery, and power-to-X jobs, although these have not been used in this study due to very few (empirical) data points.

2.2. Approach and employment factors used in the study

The following sub-sections provide an in-depth review of methodology of Rutovitz et al. (2015) (the first paragraph) and is accompanied by changes and additions undertaken in the current work (second paragraph). These sub-sections cover – the source of employment factors (*Calculation of employment factors*), assumptions on how EFs evolve into the future (*Evolution of employment factors*), inclusion of trade of fuels to differentiate import and export components of jobs (*Trade*), differentiating manufacturing to account for uneven distribution of manufactured components (*Manufacturing jobs*), the accounting for technologies not included but important in energy employment (*Share of sub--technologies*), and the comparison of the resulting employment numbers with other literature (*Comparison with other sources*). Additional information, wherever required, is provided in the Supplementary Information (SI) and indicated in the paragraphs. The limitations of the study for e.g., the limited sectors where employment is estimated is provided in section 3.4.

2.2.1. Employment factors

As mentioned in the section before, the majority of EFs are only available for OECD countries and where available, often show a spread of values. To tackle these two issues Rutovitz and Atherton (2009) i) calculated EF per technology for OECD countries by a weighted average or average spanning the country-specific studies ii) calculated the EF for non-OECD countries by assuming a regional adjustment factor. For the base year (2015) this factor is the labour productivity (measured as GDP (or value added) per worker, of the whole economy excluding agriculture) for different nations relative to OECD. The adjustment factors are assumed to be the same across the different activities and technologies. iii) For a few studies that report EFs for non-OECD countries (for specific technologies), values from step ii) are replaced.

All EFs from Rutovitz et al. (2015) for OECD countries, are taken as values for the year 2020 in the current study but updated according to recent literature (Fragkos and Paroussos, 2018; IRENA, 2017a, 2017b). Following the methodology of Rutovitz et al. (2015), for countries without empirical data (mostly non-OECD), the EF is calculated by multiplying the OECD EF from Rutovitz et al. (2015) to a regional adjustment factor. Next, wherever possible, the resulting EFs have been replaced by country-specific values using studies mentioned in Rutovitz et al. (2015), recent studies (CEEW, 2019; Rutovitz et al., 2020; The Solar Foundation, 2020), or own calculations, e.g., coal EF. Lastly, some EFs are modified for specific countries/technologies by comparing the resulting jobs from the EF approach with bottom-up regional and global studies providing job estimates. See SI section 1.1 for all these details.

2.2.2. Evolution of employment factors

To estimate jobs into the future, the employment factors need to be projected into the future. They calculate this by considering two developments – improvements in LP and decline factors.

a. Improvement in labour productivity – EF for all countries into the future evolve with the improvements in labour productivity and are assumed to be equal to (inverse of) future GDP per capita (relative to OECD). For OECD countries, the factor is 1. The data on GDP per capita comes from the energy model used in the study.
b. Decline factors – account for the reduction in EF as technologies mature. They are assumed to evolve with the changing capital costs of technologies, which is an input to the energy model. Decline factors are undifferentiated across activities, except for coal fuel supply. No decline factors are assumed for oil, gas, and nuclear fuel supply (Rutovitz et al., 2015, sec. 6).

To better understand the dynamics of the system in the future, the method is slightly simplified. The employment factors calculated IEA, 2020 are subjected to - i) (inverse of) future GDP per capita for all countries (relative to 2020), which is used as a proxy for improvements in labour productivity (SI section 2.3) and ii) capital costs of technologies relative to 2020 (SI section 2.2). Data for both comes from REMIND, except the improvements in labour productivity for coal fuel supply which are exogenous (see SI Section 1.1.4).

2.2.3. Trade

Since the import of fuels (coal, gas, and biomass) does not lead to creation of fuel supply jobs in the consuming country, it is important to differentiate between the amounts of fuel produced in the country vs. amount of fuel exported/imported.

Rutovitz et al. (2015) therefore make these assumptions for each region and time step.

Trade of coal, gas, oil, biomass, and nuclear[1] is endogenous to REMIND. This means that production/import/export of a fuel are readily available as outputs of the model. The fuel supply jobs (per region, fuel, and time step) are calculated by multiplying the employment factor with the amount of fuel produced in the country.

2.2.4. Manufacturing jobs

As for fuels, the manufacturing of components required for each technology are unevenly distributed in the world and need to be differentiated. For each region and time step, the proportion of local manufacturing and share of import from all other regions is assumed. It is also assumed that countries become self-sufficient over time. The same shares are applied for wind, solar PV, solar thermal power, geothermal power, and ocean (wave and tidal) technologies. All manufacturing for fossil fuel, biomass, hydro and nuclear technologies occurs within the region.

Instead of appropriating local vs. import shares for each region and time step, the current study assigns the share of total world production/manufacture to each region, although only for solar PV and wind. All other technologies are assumed to be manufactured domestically/regionally. These shares evolve such that those regions manufacture their own share of technology deployment locally by 2050. This assumption reflects that countries will promote domestic manufacturing to create jobs locally and for reasons of energy security; at the same time

[1] Employment factor for nuclear fuel supply is based on the secondary energy of nuclear-based electricity. Furthermore, no trade in uranium is assumed, i.e., all extraction and processing jobs are created place within the consuming regions.

income convergence assumed in the SSP2 socio-economic scenario underlying our results, and spill-over effects and diffusion of technological know-how will make manufacturing available widely. The methodology is also flexible to consider fixed manufacturing shares at current levels or other assumptions for the exploration of alternative socio-economic futures.

2.2.5. Share of sub-technologies

The energy model used by Rutovitz et al. (2015) includes sub-technologies or variants of traditional RE technologies –wind onshore and offshore; small and large hydro. Solar PV is however not differentiated into rooftop and utility.

REMIND currently includes a generic technology representation each for solar PV, solar CSP, wind, and hydro as power-generating technologies, i.e., it does not differentiate between solar PV utility and Solar PV rooftop, wind offshore and onshore, and small and big hydro. For the parametrization of costs and potentials, mostly the cheaper variants (utility scale PV, onshore wind and large hydro) have been considered, but some adjustments are done to account for additional potentials (e.g., of rooftop solar in densely populated countries like Japan and India). When the only consideration is cost, only larger and cheaper variants of the technology would be installed. In reality, different constraints, e.g., land, political feasibility, energy security etc. make it impractical to exclusively deploy the dominant variants (for e.g., Germany has 60% of its installed solar capacity as rooftop). Nevertheless, the share (in terms of installed capacity) of the alternative more expensive variants for most countries remains small. When estimating energy-related jobs, these sub-technology differentiations can play an important role because the more expensive variants tend to have higher employment factors (depending on the technology and activity) (CEEW, 2019; Rutovitz et al., 2015; The Solar Foundation, 2020).

To capture this effect to some extent, an external share controls how much of the additional and existing installation from REMIND (for solar PV, wind, and hydro), is supposed to be of the different sub-technology variants. A detailed explanation of this assumption is provided in SI Section 4.1.

Comparison with other sources.

Due to the different methods and boundaries (for e.g., between direct and indirect jobs) of measuring jobs, there is no 1:1 comparison between jobs estimates from this study with the previous literature. However, comparisons can still be useful to get an indication if the numbers from this study make sense and assess the relative confidence of estimates for different technologies/regions.

Such a preliminary comparison reveals that REMIND job estimates are well consistent to other national and global estimates (see SI section 1.2 for more a detailed comparison).

2.3. Scenario setup

The global integrated assessment model REMIND in its version 2.1 (Baumstark et al., 2021)was used to run two policy scenarios “NDC” and “1.5C” (described in Table 1). The evolution of employment factors into the future was explored by building EF-scenarios (ex-post). The eventual EF scenario selected included both capital costs and improvements in labour productivity driving the results. See SI section 2.1 on the process and explanation.

Table 1
Scenario name and description used in the study.

Scenario name	Scenario description
NDC	Reaching NDC targets (as submitted to UNFCCC 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.
1.5C	Immediate introduction of regionally differentiated carbon prices which converge in 2050, iteratively adjusted to fulfil a constraint in carbon budget (900 GtCO2) from 2011 to time of net-zero global CO2 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 century (2100).

3. Results and discussion

3.1. Future energy sector jobs

IEA, 2020, the total direct energy supply jobs in the world are around 20.4 million, with a roughly equal proportion between fossil and non-fossil jobs (Fig. 2a). These jobs are dominated by coal (4.3 million) followed by Hydro, solar PV, and Gas (~3 million each) (Fig. 2b and c). Fig. 2c shows that most of the current coal jobs are in fuel supply (purple) whereas solar PV jobs are almost equally split between construction and installation (C & I) (green), and manufacturing (rust yellow). Furthermore, fuel supply constitutes the largest share (~50%) of the current energy supply jobs (see also Fig. S19, which is directly expressed as shares).

In 2050, the total energy supply jobs decrease to 16 million under the NDC scenario and to 18.2 million with 1.5 °C policies (Fig. 2d). Independent of the policy scenario, the share of fuel supply jobs (purple) strongly decreases – from 50% IEA, 2020 (mainly in coal, biomass, oil, and gas) to 27% in NDC and 24% (mainly in biomass and oil) in the 1.5 °C scenario. Also, in absolute terms, the fossil fuel supply jobs decrease strongly in both scenarios, although the absolute fossil fuel supply differs by a factor of 2 in 2050 (see Fig. S17b). On the other hand. the share of fossil jobs decreases to 12–25% of total jobs, depending upon the scenario. In both NDC and 1.5 °C policy case, wind jobs dominate in 2050, and operation and maintenance (O & M) becomes the activity employing the most people (Fig. 2b and Fig. S19). In both scenarios, there is a steep increase in power generation and shift from fossils to non-fossils (mainly wind and solar), which accompanied by wide-scale end-use electrification reduces the need for conventional fuels (Fig. S17). Although renewable technologies require more jobs per MW,[2] their exponential uptake is also accompanied by steeply decreasing employment factors (due to decreasing capital costs and improvements in labour productivity) (Fig. S16). This eventually leads to lesser people employed directly in the energy supply sector than now.[3]

A good contrast on how employment factors eventually influence the shape of the curve is between wind and solar PV. Although installations for both these technologies increase steeply in the future (with solar growths higher than wind) (see Fig. S17), EFs for solar also have a sharper decline (Fig. S16). The net effect is that while jobs in wind increase almost linearly over time and become the largest employer in 2050 (Fig. 2b), solar PV jobs might be prone to periods of boom, bust, and eventual stagnation (Fig. 2b).

3.2. Near-term jobs

In the near term, there is a net increase in jobs for a 1.5 scenario (+838,500), compared to a net decrease in the NDC scenario

[2] Comparison across per technology per MW fails to capture fuel supply jobs for fossil technologies. The correct unit of measurement to compare employment across technologies should be per GWh. However, the point here is the rapid decrease in employment factors of VRE technologies in comparison to traditional technologies.

[3] A big caveat here is that jobs which might become significant in the future – storage, transmission and distribution, decommissioning, hydrogen production, and all jobs on the demand side, including energy efficiency have not been included due to data limitations. See Section 3.4.

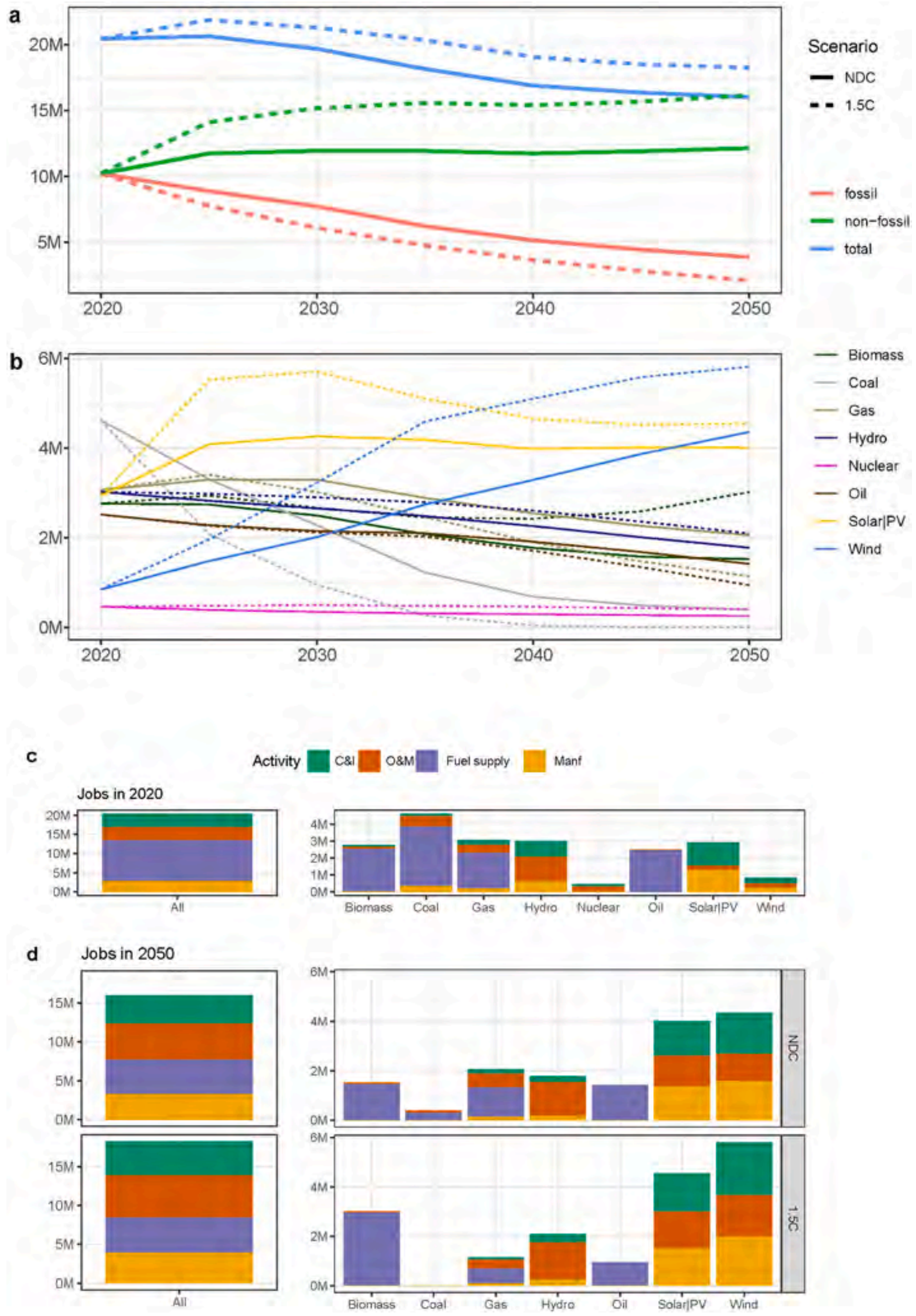

Fig. 2. Total world jobs by (a) scenario and type (Solar CSP and Geothermal not shown for clarity) (b) by scenario and technology, (c) bar plots for jobs by activity per technology IEA, 2020 and (d) in 2050 for NDC and 1.5 policy cases.

(−760,000) (in 2030 compared IEA, 2020) (Fig. 3a). Losses in the fossil sector are mainly from coal fuel supply (85–90%) and amount to 2.2–3.7 million (depending on the scenario), while gains are mainly from C & I and Manufacturing activities in solar and wind (~90%) and amount to 2.5–4.3 million (Fig. 3b).

The competing effect of capacity/production and employment factor on jobs for different technologies and scenarios can be seen in Fig. 3c. The black diagonal line represents the case where change in jobs is entirely due to change in capacity/production. The further the dot is from the linear line, the stronger the effect of the employment factor on total jobs. For e.g., while capacity increases almost 700% for solar PV in the 1.5C case, jobs increase only 94%. For coal mining in NDC while production decreases 12%, jobs decrease 51%. Comparing this with other fossil fuels (still for the NDC), we see that an increase of 9% of oil production, leads to 15% decrease in jobs, while for gas a 17% increase in production, leads to a 7% increase in jobs implying a lower effect of labour productivity improvements.[4]

3.3. Implications of the results

In Fig. 2a we showed that even with a significant expansion in

[4] This is by design. Employment factors in coal change depending upon historical trends while oil and gas employment factors change with (inverse of) GDP/capita.

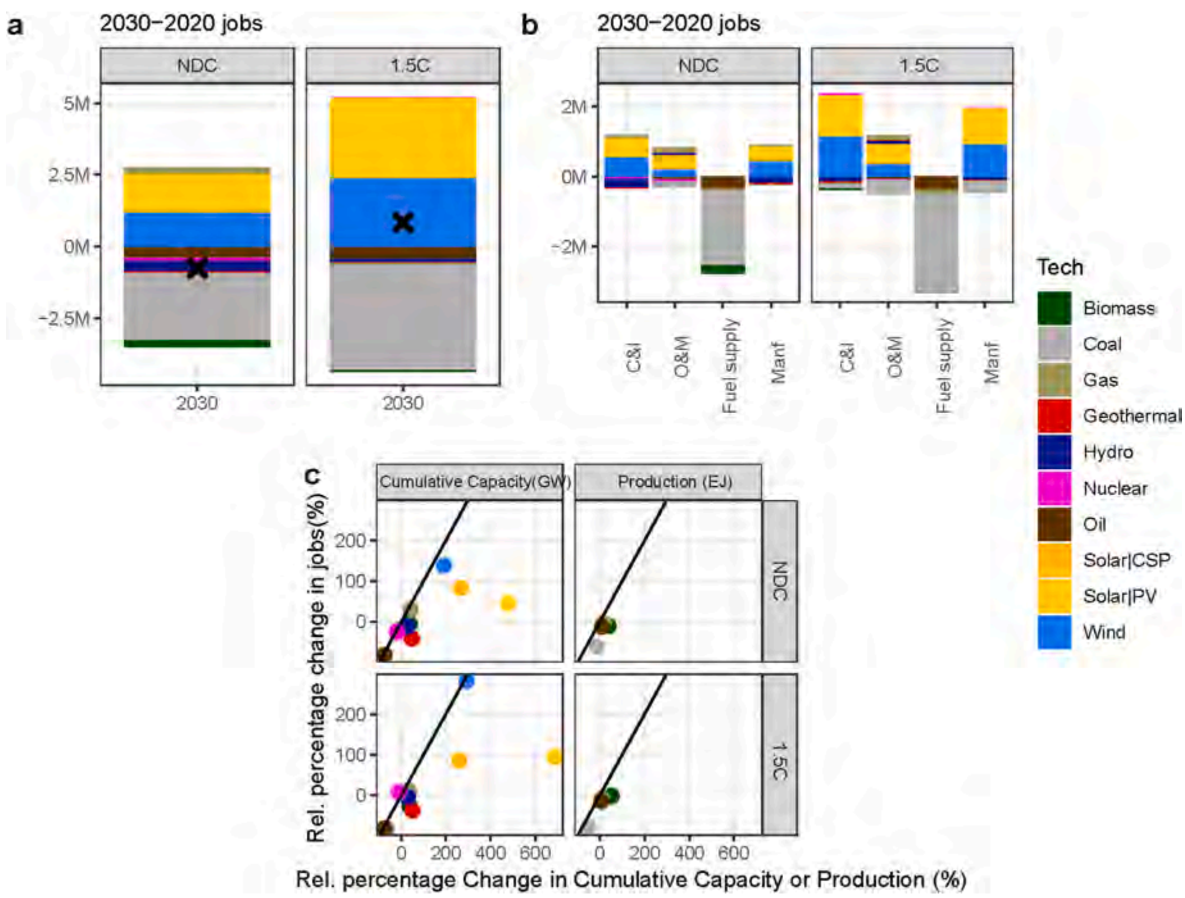

Fig. 3. Difference in Global jobs (2030-2020) for (a) different technologies (with cross denoting the net gain/loss) and (b) technologies and activities, and (c) relative percentage change in jobs vs. relative percentage change in capacity (GW)/production (EJ) (in 2030 relative to 2020) for the two policy scenarios.

renewables, energy supply jobs, after peaking around 2025, decrease because of the strong effect of increasing labour productivity and decrease in capital costs.[5] This result is not surprising. Under the assumption of decreasing capital costs, increasing wages and constant share of labour in total capital costs, employment factors must fall faster than the capital costs.

The employment-related challenges in the oncoming energy transition for both the NDC and policy cases, can be understood from Fig. 3b. In NDC, almost 2.7 million jobs are lost in fuel supply, compared to 2.5 million gained through solar PV and wind. Thus, even under an ideal assumption that all coal workers manage could be retrained to be employed in these new jobs, these will not be enough. How many of the new jobs go eventually to people who lost them depends on many factors – skill requirements and location of created and lost jobs, options for retraining and relocating, incentives and compensation. Additionally, in the case of manufacturing, not all jobs might be created locally (at least in the near term), particularly for late entrant countries that fall back in technology development. On the other side, countries currently mostly relying on fuel imports and therefore sustaining fuel supply jobs abroad can potentially increase their domestic energy-related jobs by transitioning to local renewable energy forms.

For a 1.5 scenario, the challenges already present in the NDC scenario are somewhat exacerbated. Although there is a net increase in jobs, an extra 1.3 million jobs in fuel supply will be lost over the same period. Since most of these lost jobs would be regionally concentrated, this can result in additional challenges for policy. To alleviate the related political economy concerns will require faster and more intensive engagement between firms, employees, state government and local administration. This might not be easy considering that – i) areas of and around coal mines might not be prime areas for renewable energy development (Pai et al., 2020) and thus might not immediately gain from increasing RE deployment, ii) unlike C & I and O & M jobs, manufacturing jobs are often not local, and thus wouldn't necessarily contribute to job growth, iii) Subsequent increases in the same amount of RE capacity will employ lesser people and could lead to conditions of boom and bust.

In either case, the first step in the direction of reducing challenges and increasing support of the energy transition would be constituting regional and sub-regional studies on what, how, and how much of new RE technologies could (either theoretically or economically) substitute job losses in the fuel supply (mainly coal) at a sub-regional level (see for example Alves Dias et al., 2018; Pai et al., 2020), and then progressively move to options directly outside the energy sector. These should pay attention to the fact that, i) C & I jobs could be considered as long-term jobs (and thus on par with O & M and fuel supply jobs), under increasing RE capacity, ii) sub-technologies like solar-rooftop, small-hydro often employ much more people than large-scale solar-utility and hydropower projects.

Over decades, the results show various promising aspects of large-scale RE deployment. Firstly, fuel supply jobs in fossil are progressively replaced by O & M jobs, both of which offer job stability (see Fig. S19 and Fig. S20 for share of activity until 2050). Secondly, unlike the present day where majority of supply jobs are concentrated in coal, oil, and gas-producing countries; in a RE-based energy system jobs would be more evenly spread across the whole world, with the possible

[5] Both these factors are essentially improvements in labour productivity, with the former mostly occurring outside the energy sector (e.g., artificial intelligence, drones etc.), while the latter occur mostly within the sector.

exception for manufacturing of components, though increasing transport costs in decarbonized futures and a focus to create jobs locally might incentivize stronger local production. Thirdly, within a country, energy supply will be distributed both across remote parts containing utility-scale solar and wind farms but also in cities as solar rooftop, though the relative importance of these options has implications for costs, grid requirements and broader sustainability considerations, and largely depends on policy settings.

3.4. Limitations and future research

Our result must be read with the important caveat that we only include direct energy jobs from the currently existing supply technologies. We thus do not include many other energy-related jobs on both the supply and demand sides, which could become significant into the future. These include Transmission and Distribution (T & D), Battery storage, Decentralised PV, Heating (solar thermal, heat pumps etc.), hydrogen production, and energy efficiency. Previous studies have shown that significant investment would need to go to these sectors/technologies/fuels (Bertram et al., 2021; McCollum et al., 2018), thus also highlighting their importance. Employment factors for some of these have been provided by Ram et al. (2019, 2022), however given that they are based on a few empirical studies and/or are immature technologies, their values are highly uncertain and have not been used here. Furthermore, given the specific scope of our methodology, we are unable to comment and quantify how mitigation policies would influence job numbers and structure outside (direct) energy supply, for e.g., in the automotive or chemical industry sector.

The employment factor approach relies on accurate estimation of employment factors for a technology. Moreover, an estimation of global energy supply jobs requires such values for major countries around the world. As mentioned previously, although most of the energy supply jobs exist in non-OECD countries, employment factor studies are mostly available for OECD countries. Thus, besides the need of studies calculating employment factors for both conventional and new technologies, the spatial scope needs to cover more non-OECD countries.

4. Conclusions and policy implications

Our estimation of employment in the energy supply sector was based on the employment factor approach, whose different assumptions were explored before. Using this approach, we quantified direct jobs in the energy supply sector for two scenarios – NDC (weak climate mitigation) and 1.5C (strong climate mitigation). We showed that for both policy and NDC scenarios the direct energy supply jobs decrease in the future compared to 2020, however ambitious policy jobs are higher than the latter. Secondly, the increase in cumulative solar and wind capacity, against the decrease in total fuel production means that the O & M jobs overtake fuel supply as the major share of total jobs. Lastly, in the near-term, net gains are seen only in the 1.5C policy case, however, lead to considerable losses in the coal mining sector. This exposes the trade-off of ambitious climate policy – both of increasing job losses and gains, and eventually the dichotomy of political support – in the form of winners and losers. To align both towards a strong climate ambition will require that (people/regions/firms) currently working on the fossil side are made available the opportunities in the new RE energy world or compensated through other means.

5. Data availability

The input data, including the code to produce the figures, both in the main text and SI, is available here - https://gitlab.pik-potsdam.de/amalik/energy-employment. The scenarios were prepared using the open-source integrated assessment model REMIND (https://github.com/remindmodel/remind and https://zenodo.org/record/4091409).

CRediT authorship contribution statement

Aman Malik: designed the study, designed and produced the figures, and wrote the manuscript. **Christoph Bertram:** designed the study and provided inputs to the manuscript. **Elmar Kriegler:** provided inputs to the manuscript. **Gunnar Luderer:** provided inputs to the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112642.

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Supplementary information
Climate policy accelerates structural changes in energy employment

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Contents

1 Employment factors and job estimates

1.1 Employment factors

1.1.1 Calculating employment factors

All EFs from Rutovitz et al., 2015 for OECD countries , are taken as values for the year 2020 in the current study but updated according to recent literature (Fragkos & Paroussos, 2018; IRENA, 2017a, 2017b). Following the methodology of Rutovitz et al., 2015, for countries without empirical data (mostly non-OECD), the EF is calculated by multiplying the OECD EF from Rutovitz et al., 2015 to a regional adjustment factor (section 1.1.2 below). Next, wherever possible, the resulting EFs have been replaced by country-specific values using mentioned in Rutovitz et al., 2015, recent studies (CEEW, 2019; Rutovitz et al., 2020; The Solar Foundation, 2020), or own calculations, e.g., coal EF (section 1.1.4 below). Lastly, some EFs are modified for specific countries/technologies by comparing the resulting jobs from the EF approach with bottom-up regional and global studies (Section SI 1.2.3) providing job estimates.

1.1.2 Calculating regional adjustment factors

For all those countries without an employment factor in 2020, a regional adjustment factor was used. This regional adjustment factor is the ratio of the labour productivity (excluding agriculture) for a country (lacking data) to the average OECD labour productivity (excl. agriculture).

The labour productivity (LP) is defined as the total output (GDP) per employed worker. The most updated and comprehensive data for the world on output, labour and labour productivity data is available from *The Conference Board Total Economy Database* (Conference Board, 2020). Labour productivity from this database, however, cannot directly be used to calculate the adjustment factor because developing countries often contain a disproportionally large number of people in agriculture, i.e., the labour productivity in agriculture is often much lower than other sectors (Rutovitz et al., 2015). So that this effect doesn't bias the results (which would result in higher regional adjustment factors and higher employment factors), agricultural GDP and people employed in agriculture (World Bank, 2019) were subtracted from the total GDP and total people employed respectively, to obtain a new labour productivity excluding agriculture. Since employment in agriculture for energy use (either as electricity, biogas, biofuels, or heating) is a small percentage of the total employment in agriculture in developing countries, the adjustment factor was not changed for biomass-based supply technologies. The relative LP is calculated by dividing the country-specific LP to OECD average LP. Finally, the regional adjustment factor is inverse of the relative LP. The employment factor of a non-OECD country (lacking data) is then the product of employment factor (OECD) and the regional multiplier. Note that the regional multiplier remains the same for all activities and technologies.

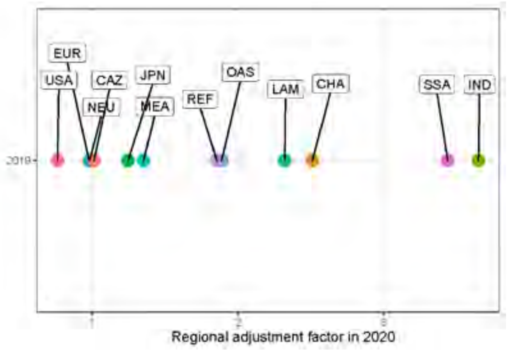

Figure S1 Aggregated regional adjustment factor (weighing on GDP) factor in 2020 based on (inverse of) labour productivity (excluding agriculture and relative to OECD in 2019). Note that this figure already aggregates the regional multipliers for various countries into REMIND regions.

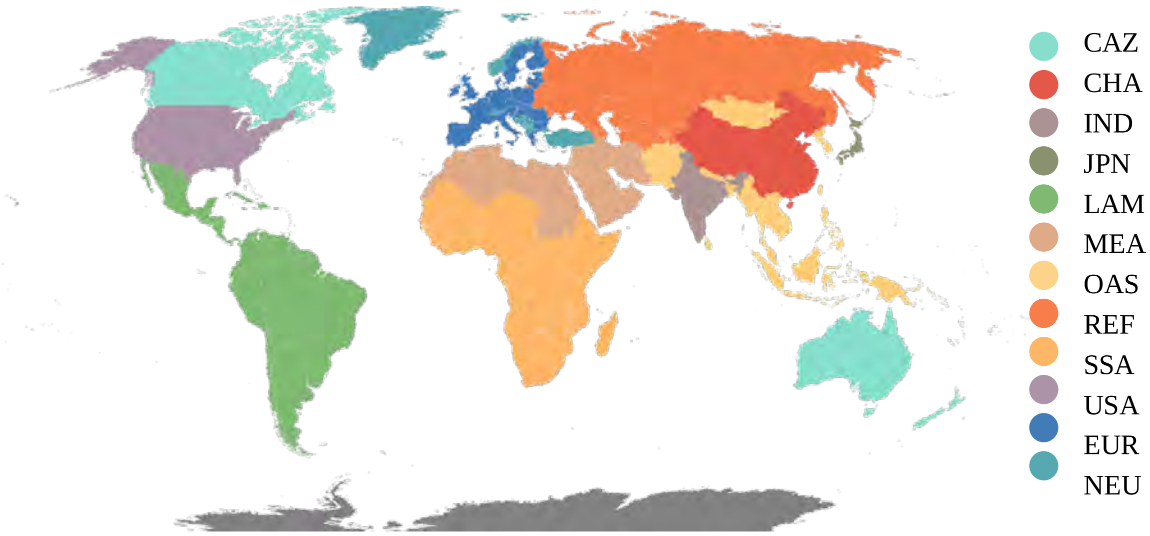

Figure S2 REMIND regions

1.1.3 Aggregating employment factors

The last step to obtain regional employment factors is to aggregate country-level results, obtained from 1.1.2 into (REMIND) regions (see Figure S2). For all technologies and activities, except fuel supply, the weighing was based on the 2019 electricity generation for that technology (data from BP 2020). For e.g., for the region EUR, employment factors for countries with higher absolute total solar power generation would be weighed more and viz-versa. For fuel supply (excluding Biomass), the weighing is based on production of that fuel (in EJ, data from BP 2020). For Biomass fuel supply, weighing is based on the employment in agriculture (Conference Board, 2020; World Bank, 2019). The results for the 12 REMIND regions are given in Figure S2 for different technologies and activities.

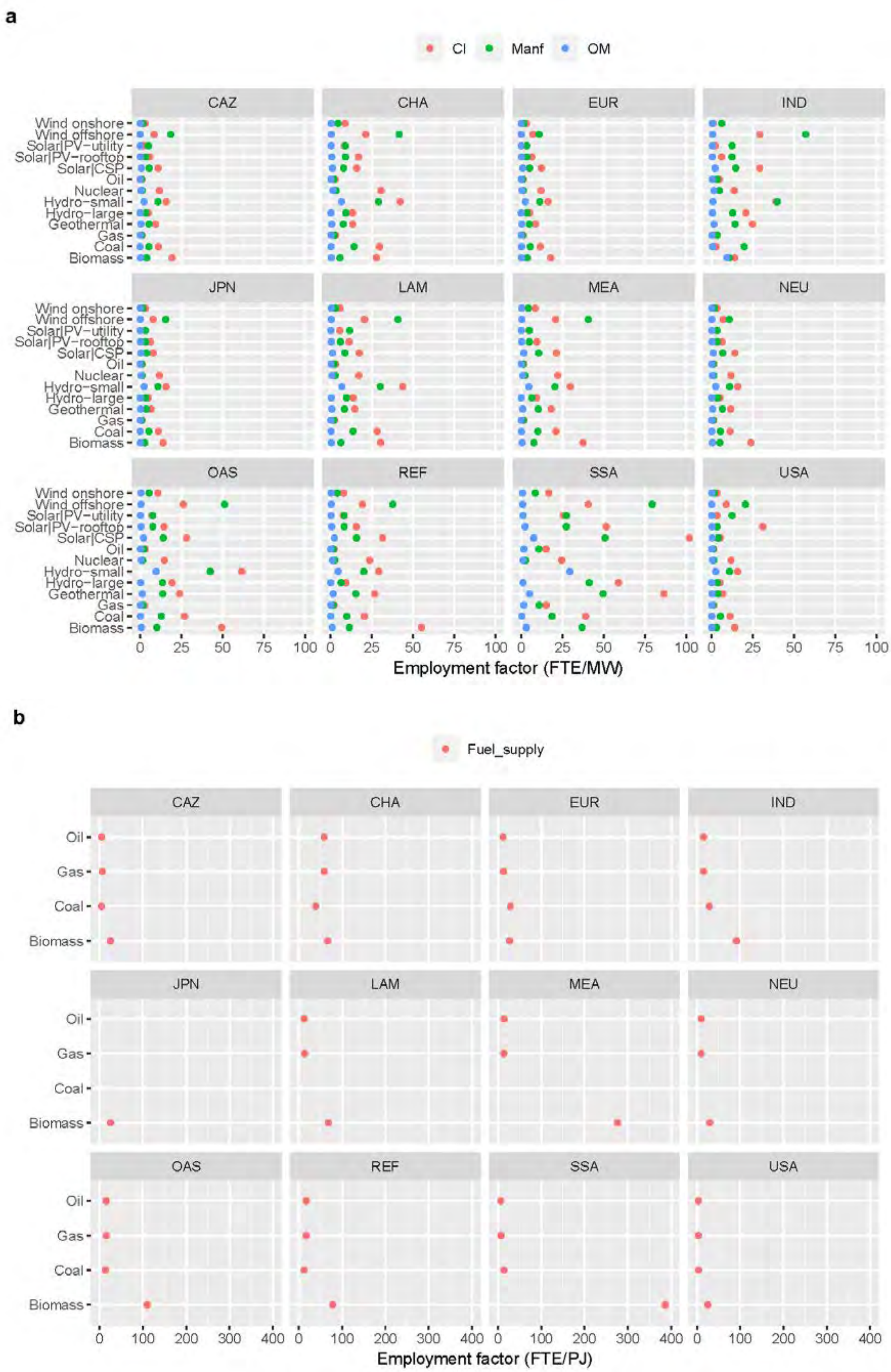

Figure S3 Employment factor by REMIND regions and technology, for (a) activity (only C & I, Manf, and O & M), (b) fuel supply for 2020.

1.1.4 Employment factors for coal fuel supply – historical and projections

Employment factors for coal fuel supply (Jobs/PJ) were calculated by using the employment in the sector (sources mentioned in Table 1) and the total production of coal (BP, 2020). The latest available EF was assumed to be the EF for 2020, e.g., if employment data for a country was available only until 2017, the EF in 2017 was assumed to be the same for year 2020. The countries covered produced 93% of the world coal (in EJ) in 2019 (BP, 2020). The values from 2020-2030 were extrapolated based on historical trends, while the EF further until 2050 were based long-term declining trends in the sector (see Table 1 for exact numbers, Figure S4).

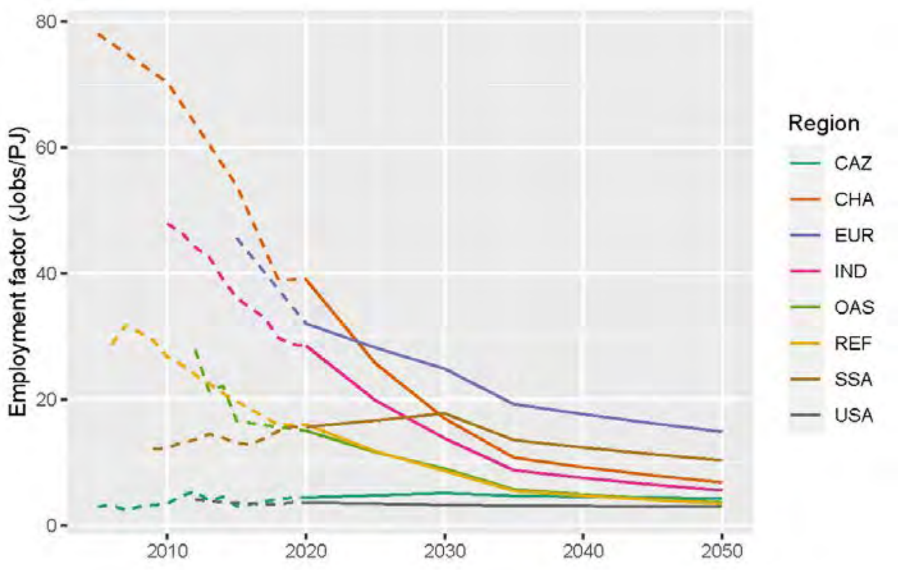

Figure S4 Historical (dashed) and estimated (solid) projections of employment factors (Jobs/PJ) for coal fuel supply for REMIND regions.

Country/Region	Share in production in 2019 (%)[1]	2020 Employment factor (Jobs/PJ)[2]	Annual change (%) 2020-2030	Annual change (%) 2030-2050	Employment source
EU	3	32[3]	-2.5	-1.5	(ILO, 2020)

[1] Data from BP, 2020

[2] Employment factors for 2020 are assumed to be the same as the data for the latest available year. E.g., for India this is 2019, China 2018 etc.

[3] Weighted average of major coal producing countries in EU

Indonesia	9	15	-7	-3	(ILO, 2020)
Russia	5.5	16	-6	-3	(Kalacheva & Savon, 2014)
South Africa	3.6	15.6	-2	-1.5	(Minerals Council South Africa, 2020)
Australia	7.8	4.4	1.5	-0.2	(Australian Industry and Skills Committee, 2017)
United States of America	8.5	3.6	-1.3	-0.3	(U.S. Bureau of Labor Statistics, 2020a)
China	47.6	39	-8	-3	(He et al., 2020)[4]
India	7.6	28.5	-7	-3	(Coal India Limited, 2019)[5]

Table S1 2020 Employment factors for coal fuel supply including projections for various countries/regions. These countries were then aggregated into REMIND regions to produce Figure S3.

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1.2 Comparison of job-estimates

Due to the different methods and boundaries (for e.g., between direct and indirect jobs) of measuring jobs, there is no 1:1 comparison between jobs estimates from the literature (both peer-reviewed and grey) and this study. However, comparisons (when the main assumptions are clear) can still be useful to get an indication if the numbers from this study make sense and assess the relative confidence of estimates for different technologies/regions. Figure S4 and S5 shows the comparison of comparison of global and regional jobs from REMIND in 2020 using the employment factor approach and other sources. Data behind the figures is available on https://gitlab.pik-potsdam.de/amalik/energy-employment.

1.2.1 Calculating jobs from employment factors

The schematic depicting the calculation of energy supply jobs for a particular year is shown in Figure 1 of the main paper. Due to the temporal nature of C & I (construction and installation) and manufacturing jobs, some studies (Rutovitz et al., 2020) divide the resulting job numbers for these activities with the average construction period to get the jobs in that year. This approach, however, has not been followed in this paper and has important implications for bottom-up comparisons. Jobs

[4] The data includes employment in both coal power plants and coal fuel supply. It was assumed that 94% of total jobs were in coal fuel supply, rest in coal power plants,

[5] CIL report only includes employees of CIL, which produces 80% of India's coal (Coal India Limited, 2019). Thus, EFs here are only for CIL.

for technologies with especially long construction durations like hydro and nuclear might be over-estimated because employment anticipated from under-construction capacity in the coming years is already calculated in 2020

1.2.2 Scope of jobs in studies

IRENA publishes "The Annual Review of Renewable energy jobs" since 2013. The data includes global direct and indirect jobs for the RE sector. Direct jobs are defined as *"employment that is generated directly by core activities without considering the intermediate inputs necessary to manufacture renewable energy equipment or construct and operate facilities. These directly involved industries are also called renewable energy industries (sectors)"* and indirect jobs as "*employment in upstream industries that supply and support the core activities of renewable energy deployment. Usually, these workers do not consider themselves as working in renewables; they produce steel, plastics or other materials, or they provide financial and other services"* (IRENA, 2014).

The "State of the Renewable Energy" annual reports prepared by EuObserver also measures both direct and indirect employment for EU countries. Direct employment is defined as "*those in renewable equipment manufacturing, renewable plant construction, engineering and management, operation and maintenance, biomass supply and exploitation"*, whereas indirect employment as *"employment in secondary activities, such as transport and other services"* (EuObserver, 2018).

IEA job estimates used in (IEA, 2020) also calculate global direct and indirect jobs in energy supply. Direct jobs are "*those that are created to deliver a final good or project*" and indirect jobs as *"supply chain jobs created to provide inputs to a final project or product"*. Unlike the previous two reports, data from this report has been extracted from the text.

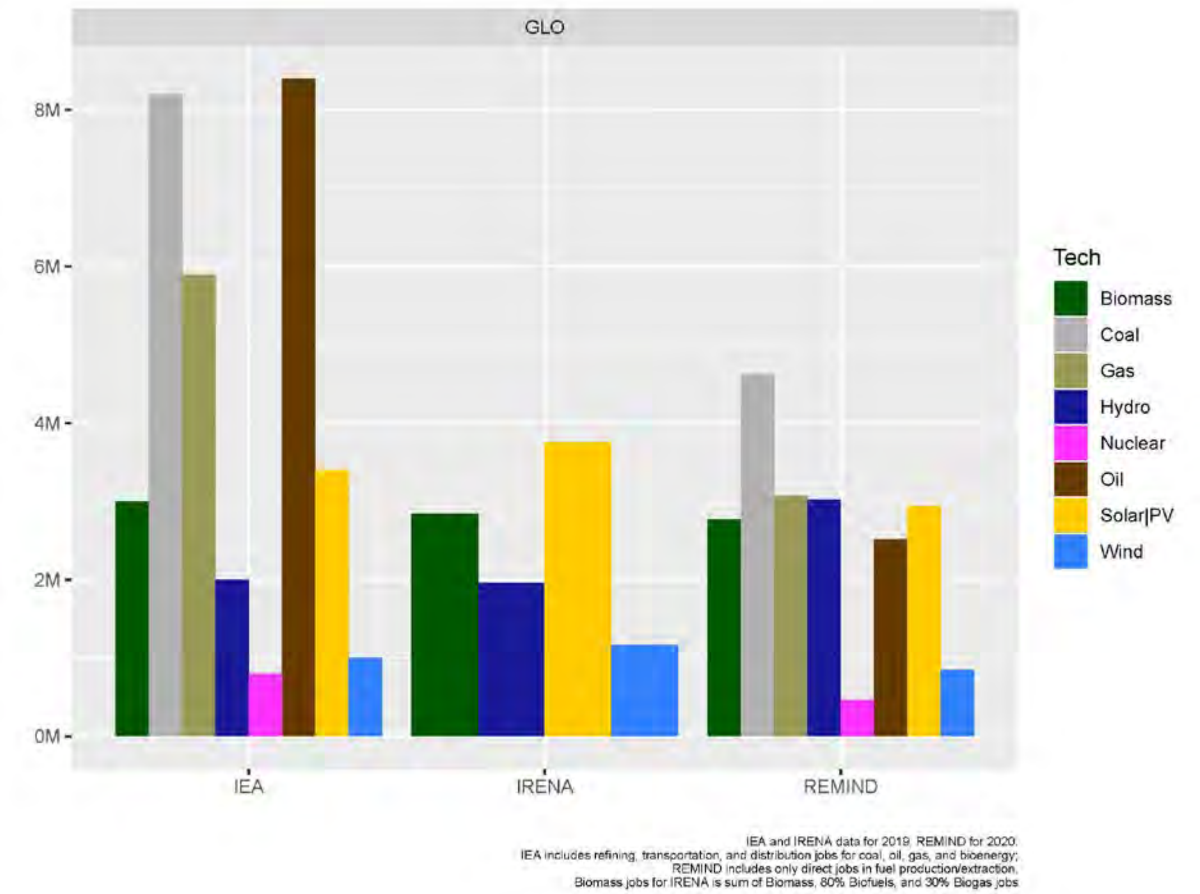


Figure S5 Comparison of global job estimates in different energy supply technologies from various sources, including REMIND. Values for IEA have been extracted from (IEA, 2020)

1.2.3 Comparison of global job estimates

Because of the wider scope of jobs for both IEA and IRENA (direct and indirect) compared to REMIND, jobs in the former can be assumed to be as an upper bound for REMIND jobs. Figure S4 shows the comparison between the three. Coal, oil, and gas (fuel supply) jobs in IEA include jobs in production, transportation, and distribution, whereas REMIND (fuel supply) jobs only include resource extraction, hence the large difference between the two. IRENA divides bioenergy jobs into solid biomass, biofuels and biogas jobs; with biofuels also including jobs in refining. Since the current methodology does not include refining jobs or biogas, only the jobs in biomass fuel supply (planting and harvesting) have been considered from IRENA for the comparison. This was done by assuming 80% of the jobs in biofuels, where most jobs are still in fuel supply (IRENA, 2020a), but only 30% in biogas, where most jobs are presumably in C & I, Manufacturing, and O & M (operation and maintenance) of biogas plants. Considering this, REMIND numbers stay at or below values from IRENA and IEA.

1.2.4 Comparison of regional jobs estimates

For comparison at a regional level, the 12 REMIND regions were divided into 3 countries (USA, IND, CHN) and 2 regions (EUR and Rest of World – RoW) and additional sources were added, where available.

Figure S5 shows one problem of using uniform relative labour productivity as a proxy for employment factor. Despite excluding agriculture to calculate the relative labour productivity, India and Rest of the World (Figure S5b and Figure S5c), still have higher employment for biomass in REMIND compared to IRENA. On the other hand, jobs for China (Figure S5e) is at or below the numbers from IRENA.

The job estimates from REMIND for other technologies and regions are at or below the estimates from REMIND and/or other data sources, except hydropower for which a comparison is difficult because the current methodology compresses jobs spread over subsequent years into one year (already mentioned in Section 1.2.1)

Note that this comparison is a work in progress and other data sources will be added as and when made available.

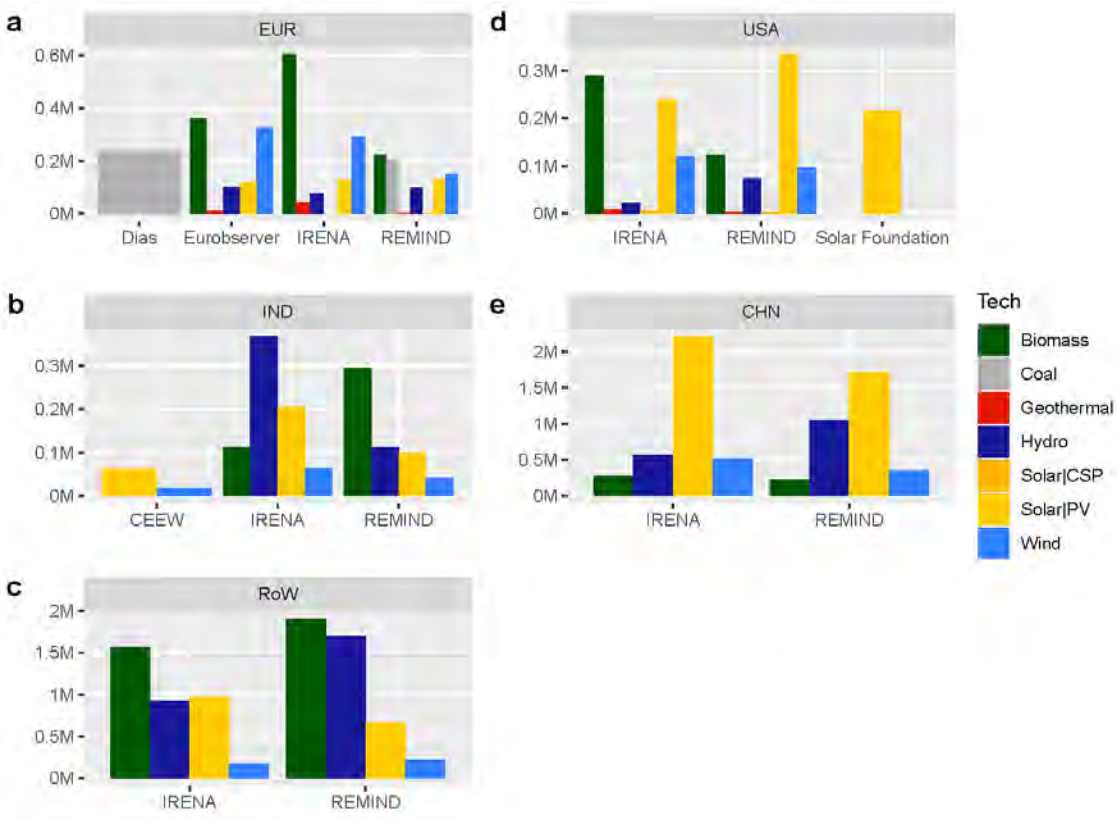


Figure S6 Comparison of job estimates for various technologies and Countries/Regions (a-e) between REMIND and other sources. Data from Dias et al. is from 2015 (only direct jobs in coal fuel supply and electricity), Euobserver data from 2018 (direct and indirect jobs), IRENA for 2018-2019 (direct and indirect jobs), Solar foundation for 2019 (only direct jobs incl.), CEEW for 2018 (direct jobs), REMIND for 2020 (direct jobs).

2 Evolution of employment factors

Starting from the employment factors in 2020 (section 1.1), employment factors evolve based on certain assumptions. Rutovitz, Dominish, and Downes 2015 assume that employment factors evolve based on i) the capital costs of technologies, and ii) for non-OECD countries, the regional adjustment factor evolves with (inverse of the) GDP per capita (relative to OECD). This study uses the same approach with one main difference - the regional adjustment factors evolve with (inverse of) GDP per capita for all regions, and not relative to OECD.

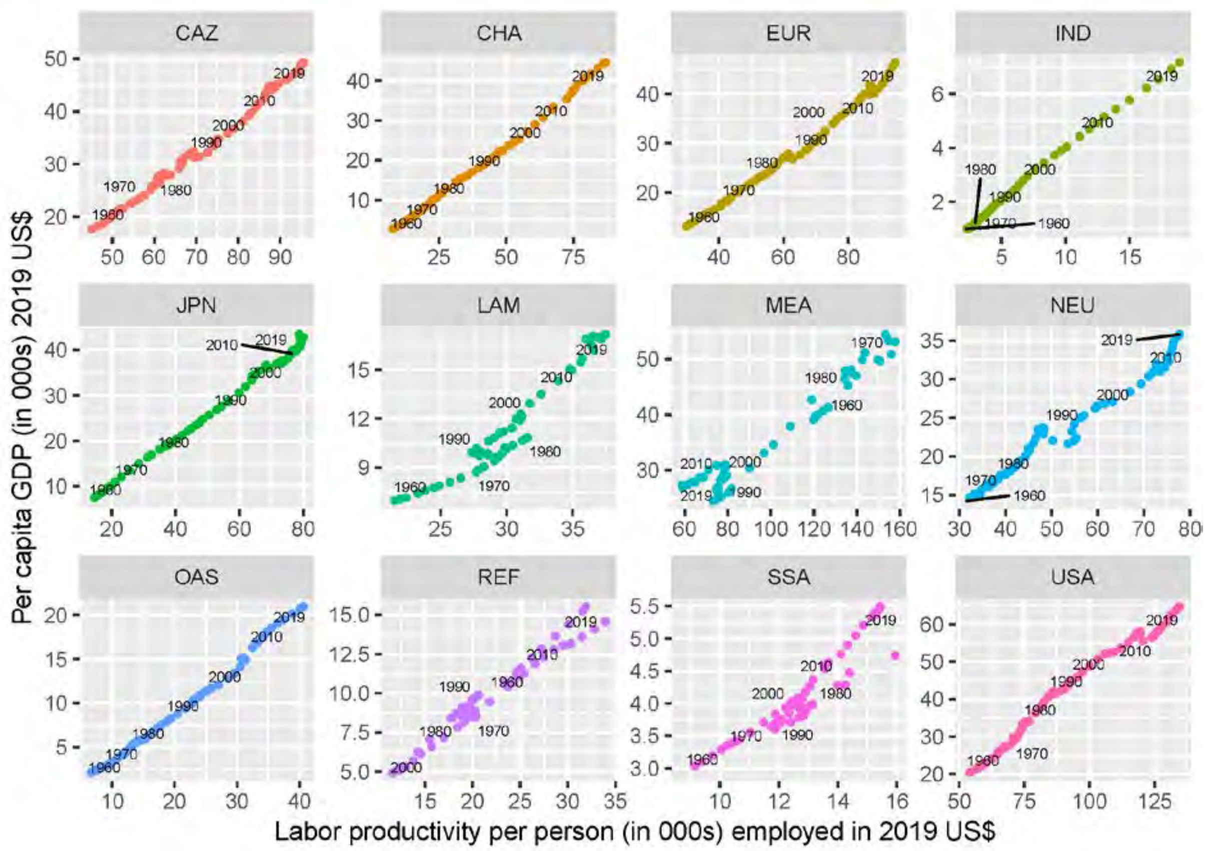


Figure S7 Per-capita GDP (in 000s US $ 2019) vs. Labour productivity per person employed (in 000s US$ 2019). The data for around 130 countries was available from The Conference Board Total Economy Database, July 2020. These countries were grouped into (REMIND) regions and their values averaged.

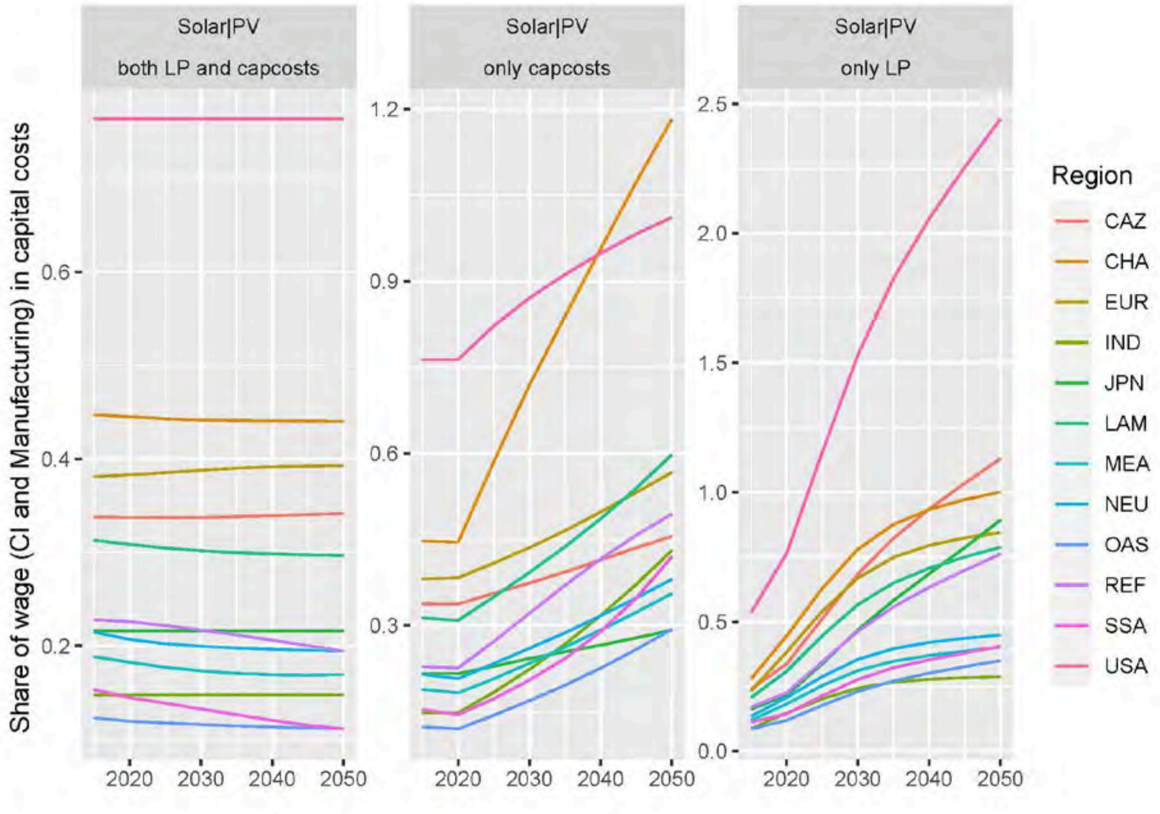


Figure S8 Share of wage in capital costs (considering employment factors in both C & I and Manufacturing) for different EF scenarios, for a 1.5C Policy case for Solar PV. The annual per capita wage for each employee in a region is assumed to be the GDP per capita of that region. Capital costs for Solar PV are taken from REMIND.

2.1 Choosing the main EF scenario

Based on the assumptions that the EF depends on the labour productivity (LP) and capital costs, we create three EF-scenarios. Merits and demerits of each are mentioned below and a table summarising them is available as Table S2.

1. EF scenario “Only LP” (labour productivity) represents the case where the employment factors (for all technologies and activities) evolve depending on the (inverse of) GDP per capita. The GDP per capita is linearly correlated to the labour productivity (when expressed in $ output per worker) (see Figure S7). Thus, as countries get richer, not only does labour gets more skilled but the factor of production shifts from labour to capital leading to an increase in labour productivity. Higher GDP growth rates for non-OECD countries also lead to a faster reduction in employment factors for these countries. The problem with this approach is twofold, i) it applies a uniform rule across all technologies and activities, failing to include their different nature and stage of maturity, and ii) it underestimates the rate of EF decrease for key technologies (like solar PV), Figure S8 illustrates this

point - assuming that EF decreases only with improvements in labour productivity, the share of labour costs in total capital costs becomes close to or greater than 1[6], leading to an impossible result.

2. EF scenario “only capital costs” represents the scenario where the EFs evolve only with the capital costs of a technology. In REMIND, regionally differentiated capital costs converge in 2050 (see SI section 2.2). A few technologies, namely solar PV, wind, and solar CSP also include learning, i.e., the capital costs decrease depending on the cumulative capacity. Capital costs evolution of technologies are applied to the C & I, Manufacturing and O & M stages while fuel supply employment factors (except for coal) do not change. The main advantage of this approach is that unlike #1, it treats technologies differently and only changes EF for activities not involving fuel supply. The main disadvantages of this approach are – i) that capital costs for some technologies (in certain regions) increase in the future (Figure S8b) implying an increase in Jobs per MW. This is likely improbable given that increasing wages and mechanization leads to lesser people employed in an activity, ii) it provides no method to fuels involving production/fuel supply.

3. Both LP and capcosts – Under this scenario, EFs evolve with both the capital costs and labour productivity, resulting in a faster decline in EF for key technologies like solar PV and wind This makes sense - under the assumption of decreasing capital costs and increasing wages, employment factors need to decrease faster than the rate at which capital costs decrease. The combination of the two can be thought of as a union between forces influencing employment factors inside and outside the industry. While capital costs evolution considers developments within the industry, developments outside the energy supply industry but which affect still its production, e.g., artificial intelligence, are considered through the labour productivity term.

A summary table (Table S2) is shown below.

EF scenario	**Description**	**Pros**	**Cons**
Only LP	EF evolution depends upon Improvements in labour	Provides a way to account for EF decrease for both fuel supply and non-fuel supply activities	• Doesn’t differentiate between technology or activity • For some rapidly evolving technologies, the share of

[6] The average wage was assumed to be the GDP per capita (except for USA, where it was taken as 0.9 times the GDP per capita (U.S. Bureau of Labor Statistics, 2020b)) and capital costs data was from REMIND.

	productivity only		wage in total capital costs might become close to or more than 1 (see SI).
Only capcosts	EF evolution depends upon decline factors based on capital costs	Treats technologies differently	• Provides a way to account for EF development only for non-fuel supply activities (i.e., those with a capital costs) • Capital costs for some region/technology combination might increase in the future, thus implying increasing employment factors.
Both LP and capcosts	Both improvements in LP and decrease in capital costs	• Accounts for fuel supply activities. • Accounts for region/technologies with increasing capital costs.	• Might exaggerate the EF decline in certain technologies

Table S2 Showing the pros and cons of the different EF scenarios

2.2 Sensitivity analysis of EF-scenarios

The main paper only considers results using the main EF-scenario. Results from other EF-scenarios (as mentioned in Table S2) are shown in Figures S9 to S12.

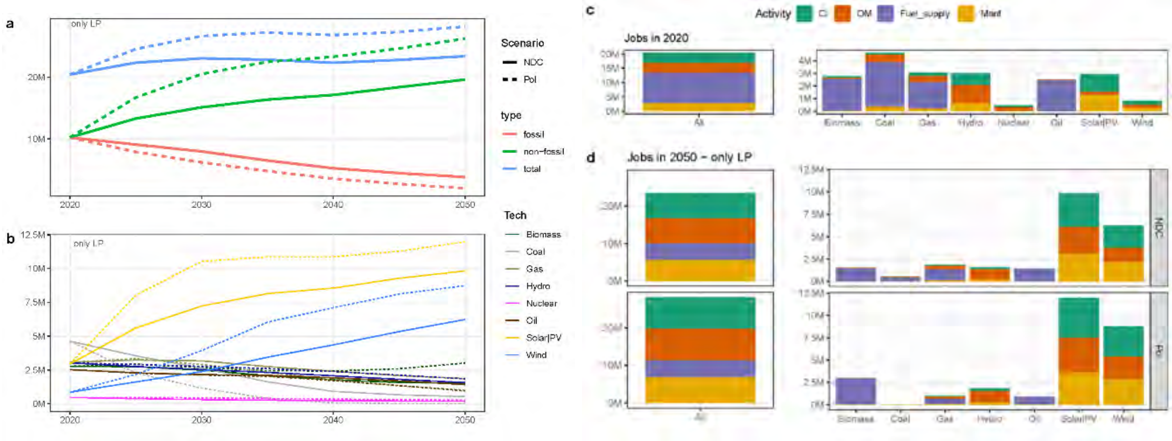


Figure S9 Total jobs by type – fossil and non-fossil for the EF-scenario (only LP) for weak (NDC) and strong (1.5C) policy scenarios

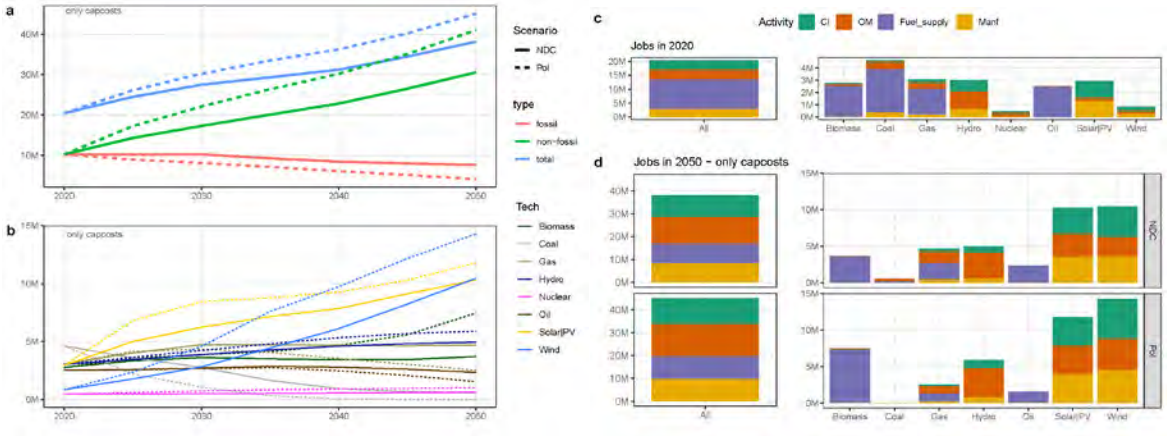


Figure S10 Total jobs by type – fossil and non-fossil for the EF-scenario (only capcosts) for weak (NDC) and strong (1.5C) policy scenarios

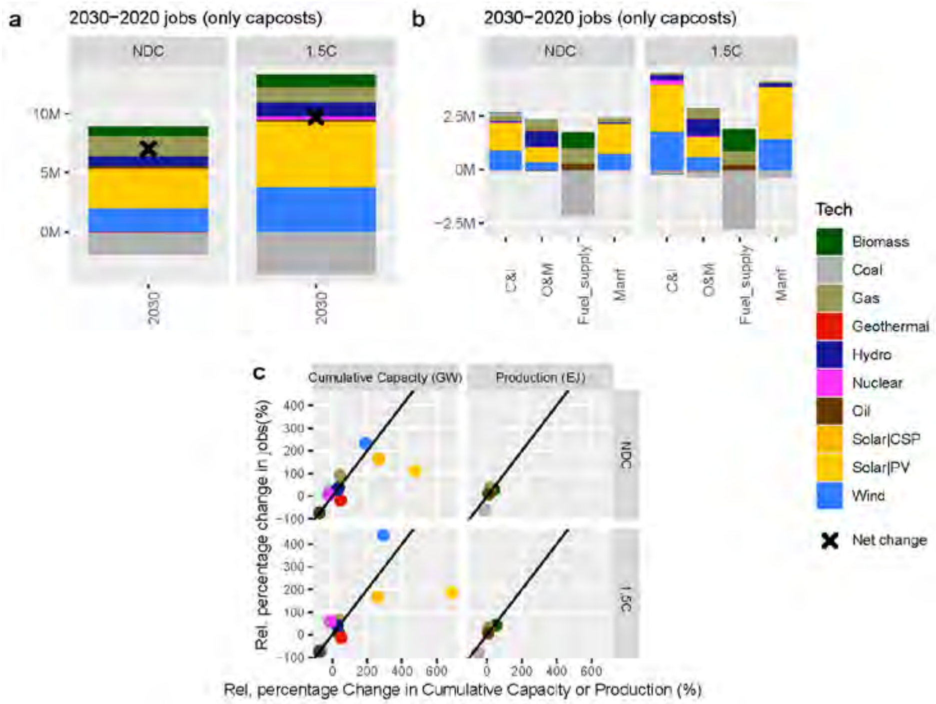


Figure S11 (a) Difference in Global jobs (2030-2020) for different technologies (with cross denoting the net gain/loss) and (b) activities and (c) relative percentage change in jobs vs. relative percentage change in capacity/production (in 2030 relative to 2020), for EF scenario – only LP

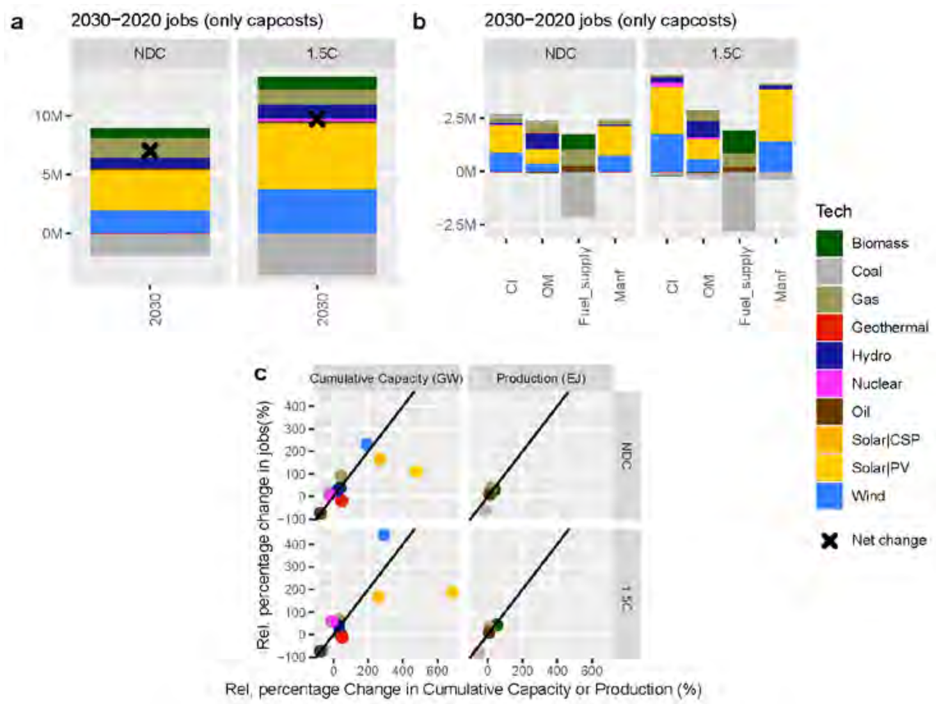


Figure S12 (a) Difference in Global jobs (2030-2020) for different technologies (with cross denoting the net gain/loss) and (b) activities and (c) relative percentage change in jobs vs. relative percentage change in capacity/production (in 2030 relative to 2020), for EF scenario only capcosts

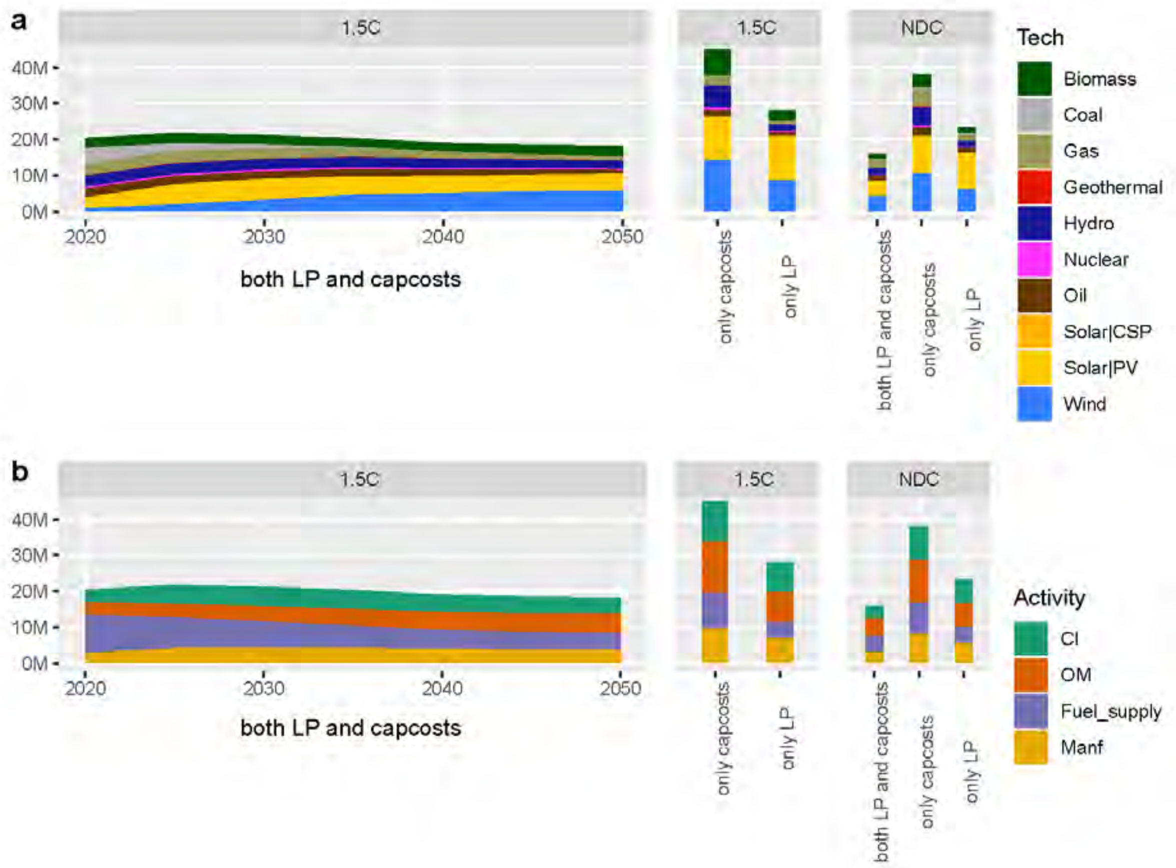


Figure S13 Area plots for total jobs by EF-scenario and scenarios by technology and activity, in 2050

2.3 Capital costs

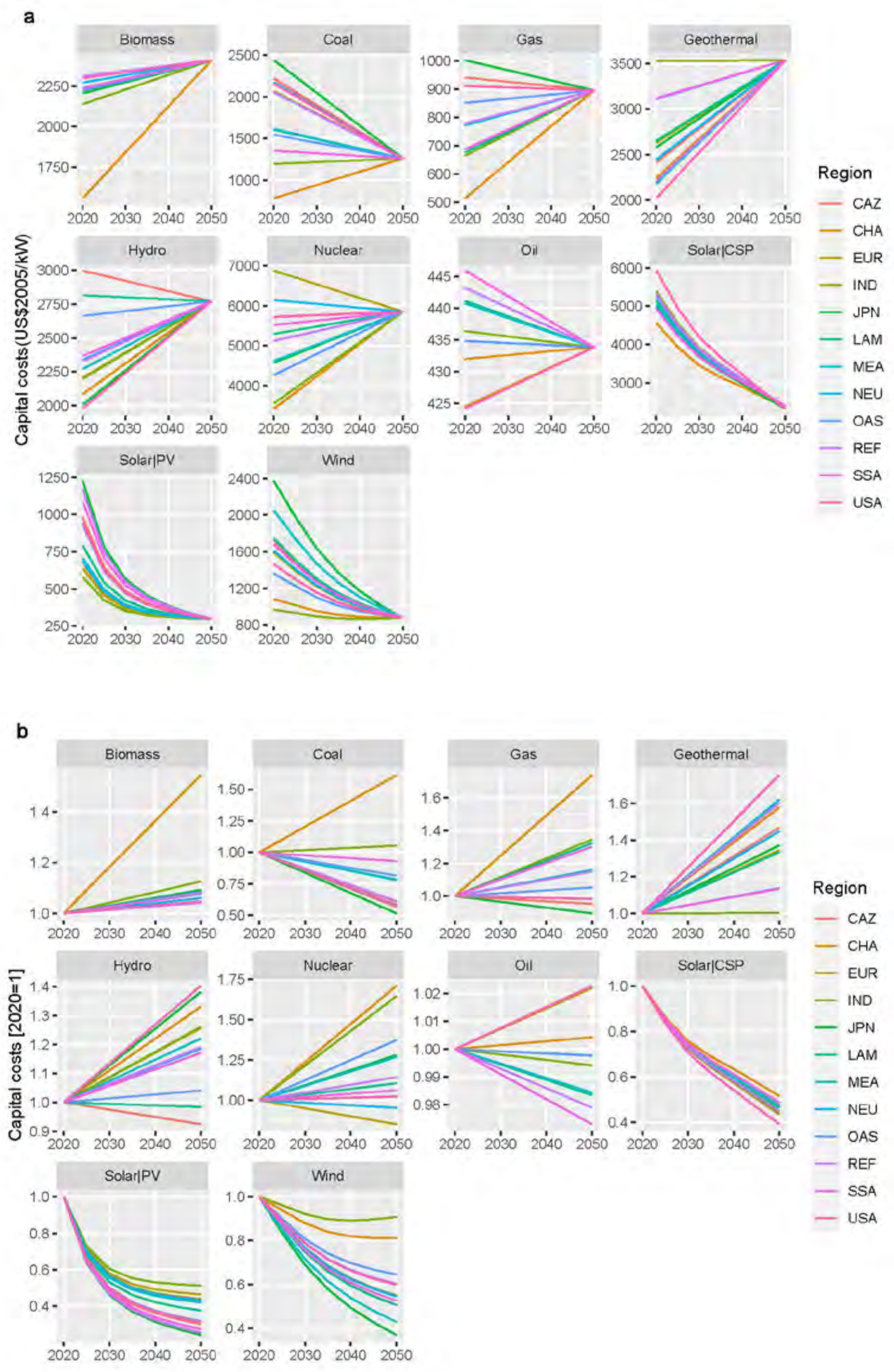


Figure S14 Regionally aggregated capital costs (a) absolute and (b) relative for various technologies from REMIND.

2.4 GDP per capita

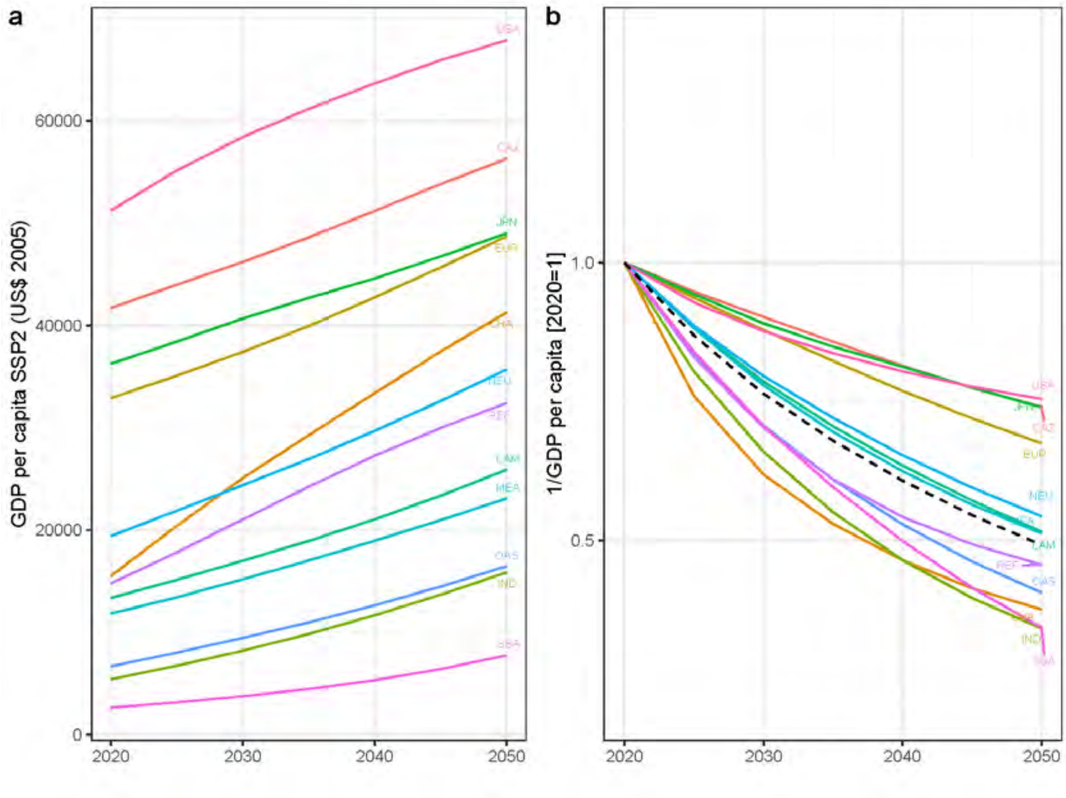
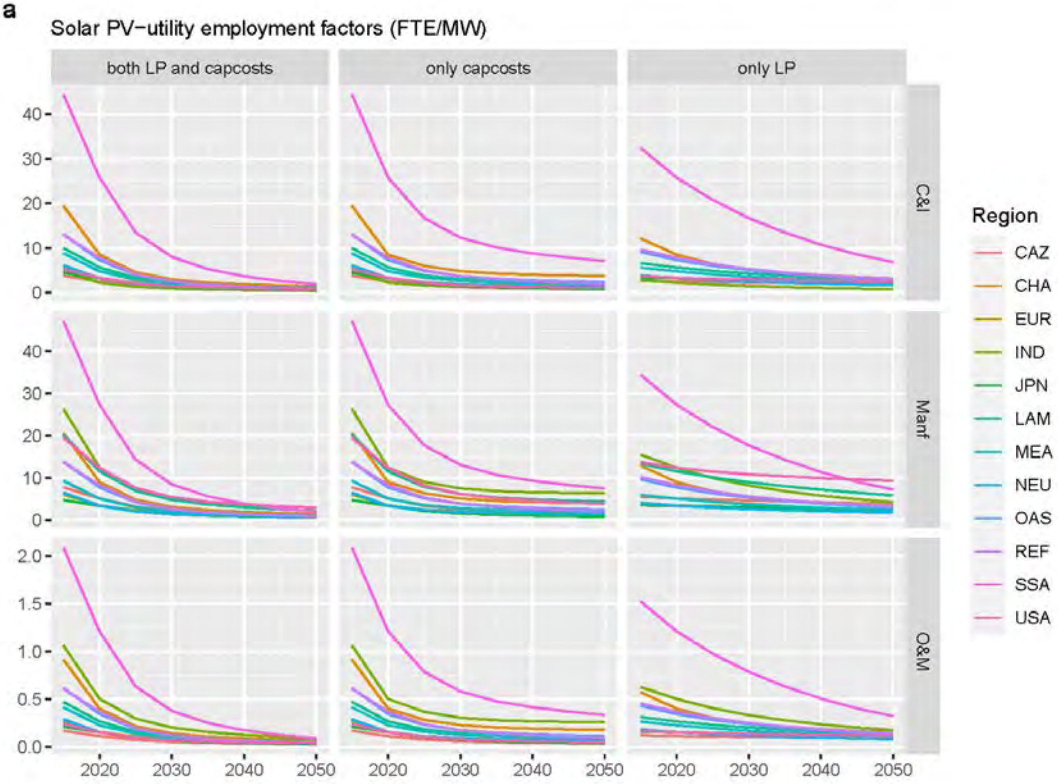


Figure S15 Absolute (a) and inverse of (b) GDP per capita (relative to 2020) for REMIND regions (SSP2). The black dashed line in b represents the average of all regions.

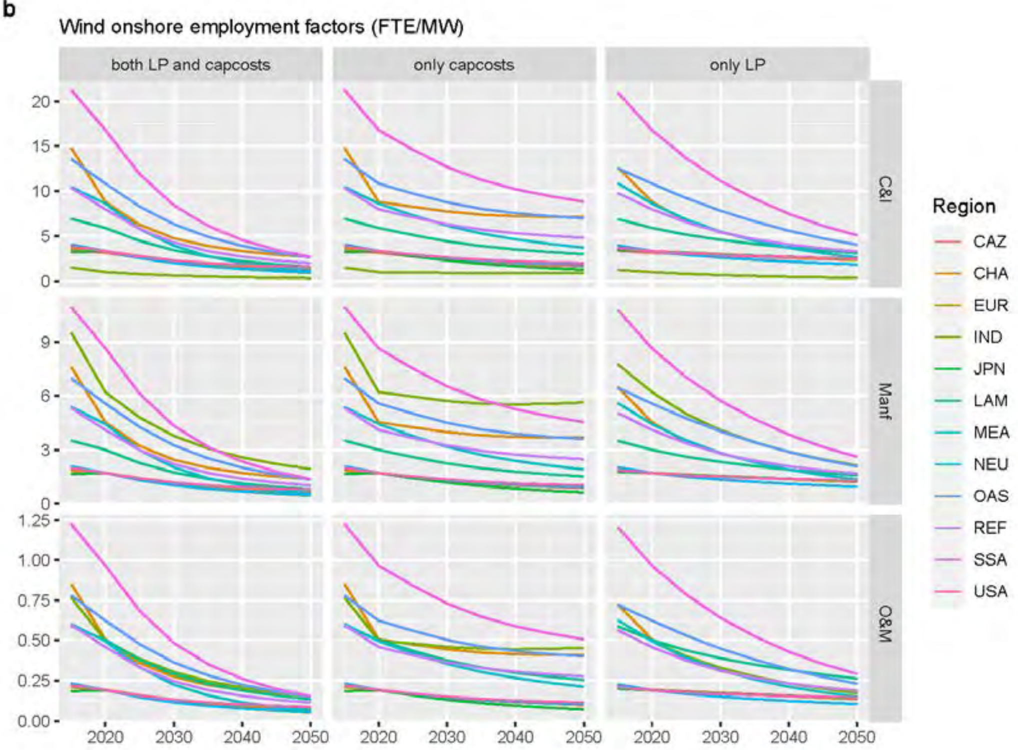
2.5 Evolution of employment factors for key technologies

a



Solar PV−utility employment factors (FTE/MW)
both LP and capcosts
only capcosts
only LP
C&I
Manf
O&M
Region
CAZ
CHA
EUR
IND
JPN
LAM
MEA
NEU
OAS
REF
SSA
USA
2020
2030
2040
2050

b



Wind onshore employment factors (FTE/MW)
both LP and capcosts
only capcosts
only LP
C&I
Manf
O&M
Region
CAZ
CHA
EUR
IND
JPN
LAM
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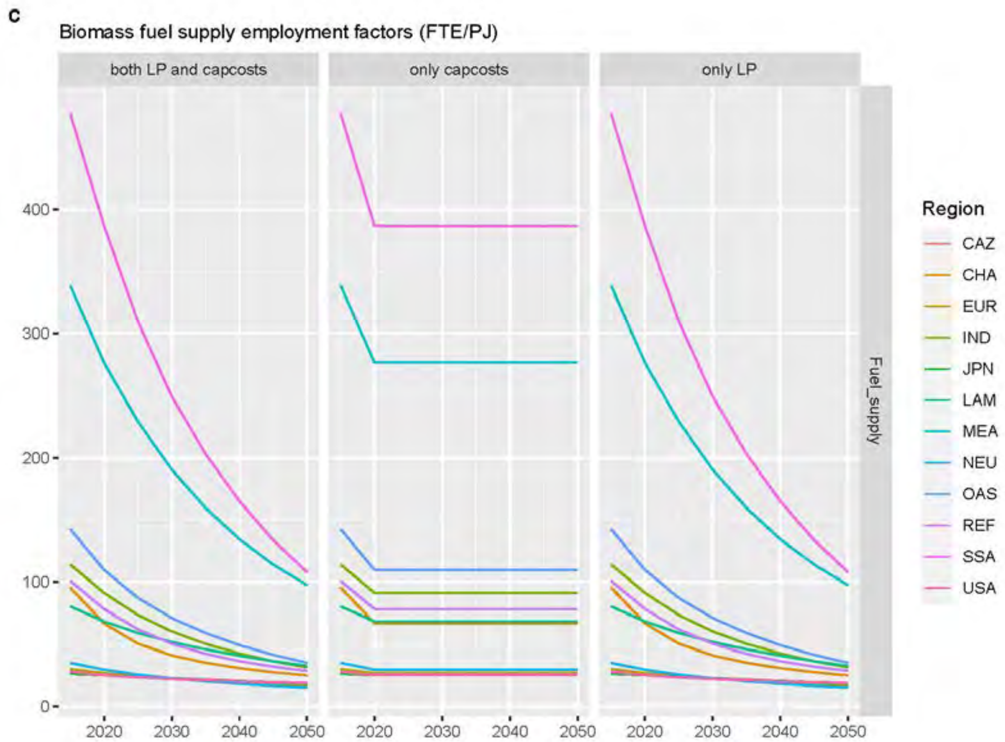
2020
2030
2040
2050



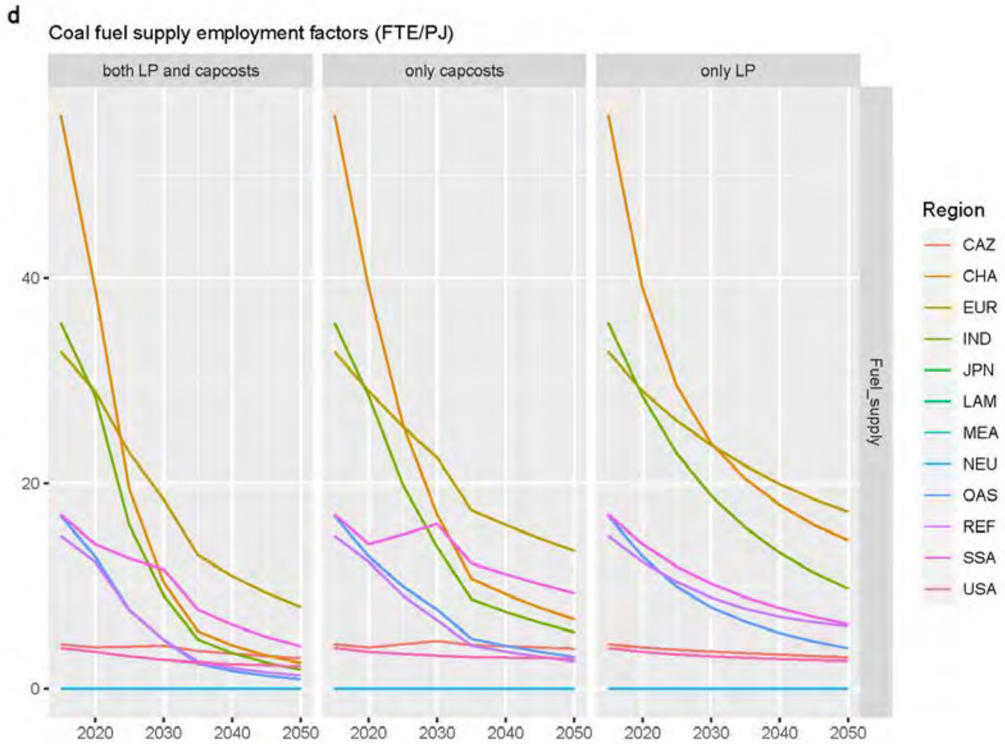


Figure S16 Employment factors for a) Solar PV-utility, b) Wind onshore, c) Biomass Fuel Supply, and d) Coal Fuel supply, classified by EF scenario and activity.

3 Capacity and Generation from REMIND

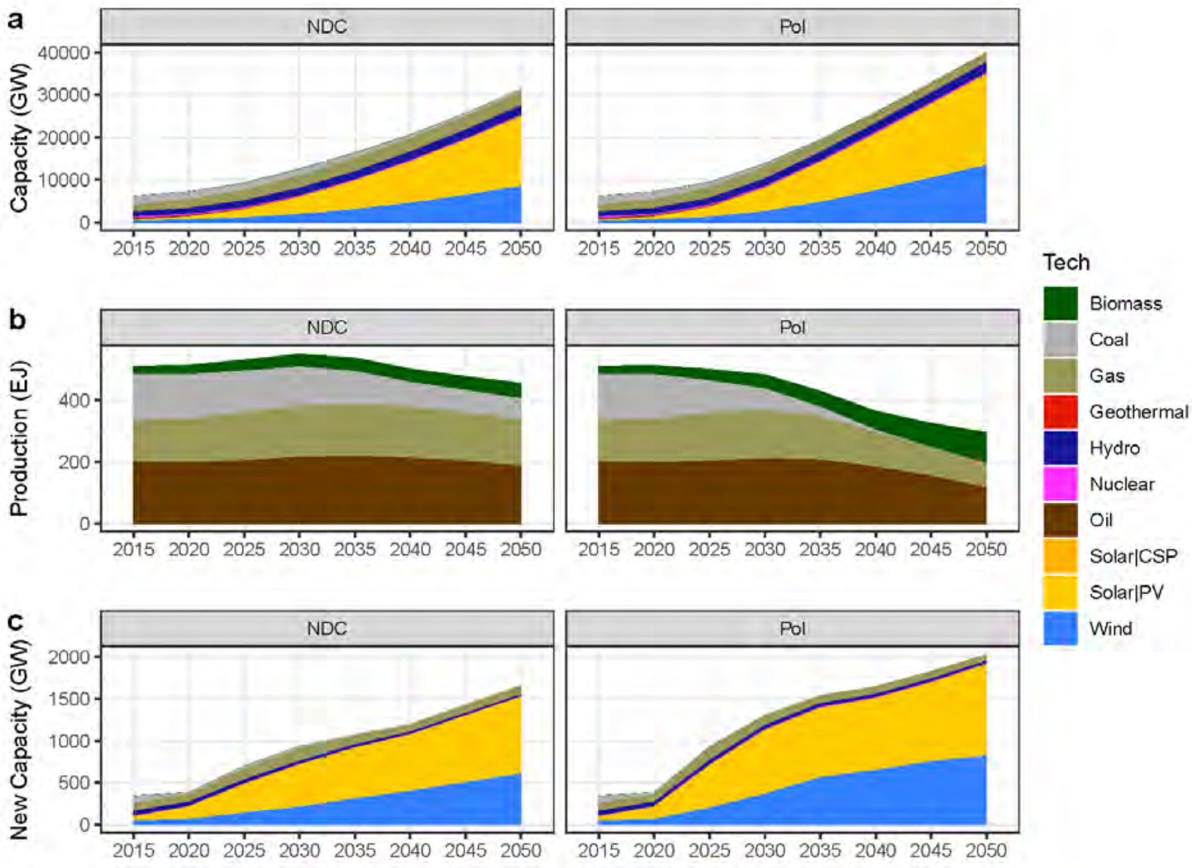


Figure S17 (a) Total cumulative capacity (GW), (b) Production (EJ), and (c) New or added capacity from REMIND until 2050 for the two scenarios - NDC and Pol (1.5C).

4 Miscellaneous

4.1 Share of sub-technologies

Sub-technologies refer to minor forms of a main technology which are not considered in REMIND. These include solar-pv rooftop, small hydro, and wind offshore. REMIND numbers are assumed to be the sum of both the major and minor form, i.e., for e.g., solar pv_{REMIND} = solar pv-utility + solar-pv rooftop. Thus, to break these down, shares of the respective forms are required. The shares in 2020 are assumed to be from the latest data from IEA 2019 and IRENA 2020b.

The assumption of how the shares evolve in shown in Figure S18 for the 12 REMIND regions. It is assumed that for all countries, solar rooftop PV accounts for 30% of total solar PV installations in 2030 (shares change linearly), except for Indian and Japan where a share of 40% is assumed to account for the unavailability of large tracts of land needed for large solar farms. For all countries, the shares do not change after 2030.

For wind offshore, top 20 countries with the longest coastline[7] get 30% share in 2050. For countries without a shoreline/landlocked[8], there is no wind offshore. For all other countries, a 10% share in 2050 is assumed. The aggregated regional shares are given in Figure S14.

For small hydropower, the share is assumed not to change over time.

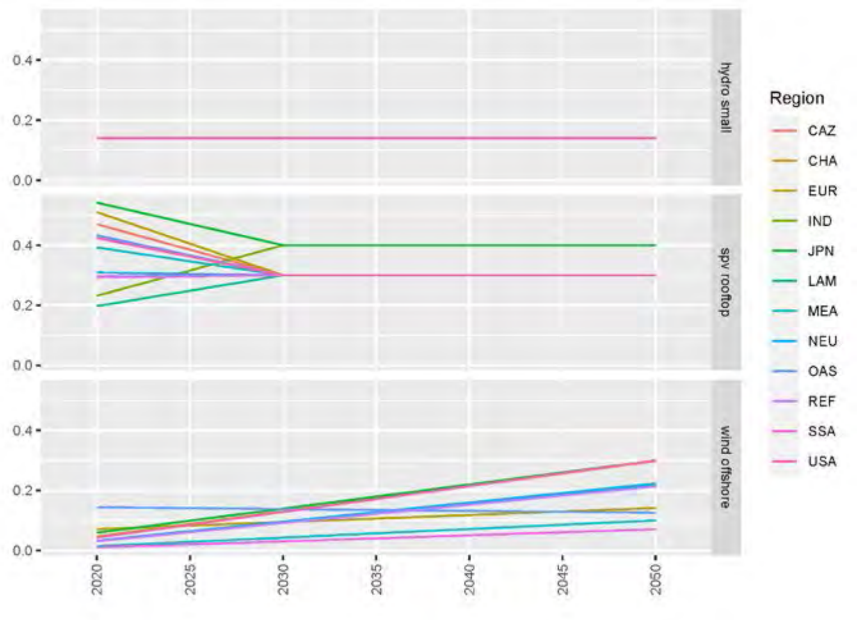


Figure S18 Historical and projected share of "sub-technologies" assumed in the study. The data for 2020 is (actually) from 2018. Shares are calculated by dividing the total "sub-technology" capacity to the total technology capacity. Total solar, wind, and hydro capacity from IRENA (2020). Distributed spv, wind offshore and small hydro capacity from (IEA Renewables 2019), and IRENA 2020 respectively.

4.2 Share of activity in total jobs

[7] These are Canada, Norway, Indonesia, Greenland, Russia, Philippines, Japan, Australia, United States of America , Antarctica , New Zealand , China , Greece , United Kingdom , Mexico , Italy , Brazil , Denmark , Turkey , India. Data from https://www.citypopulation.de/en/world/bymap/Coastlines.html

[8] These are Monaco , Afghanistan , Andorra , Armenia , Austria , Azerbaijan , Belarus , Bhutan , Bolivia , Botswana , Burkina Faso , Burundi , Central African Republic , Chad , Czech Republic , Eswatini , Ethiopia , Hungary , Kazakhstan , Kyrgyzstan , Laos , Lesotho , Liechtenstein , Luxembourg , Malawi , Mali , Moldova , Mongolia , Nepal , Niger , North Macedonia , Paraguay , Rwanda , San Marino , Serbia , Slovakia , South Sudan , Switzerland , Tajikistan , Turkmenistan , Uganda , Uzbekistan , Zambia , Zimbabwe

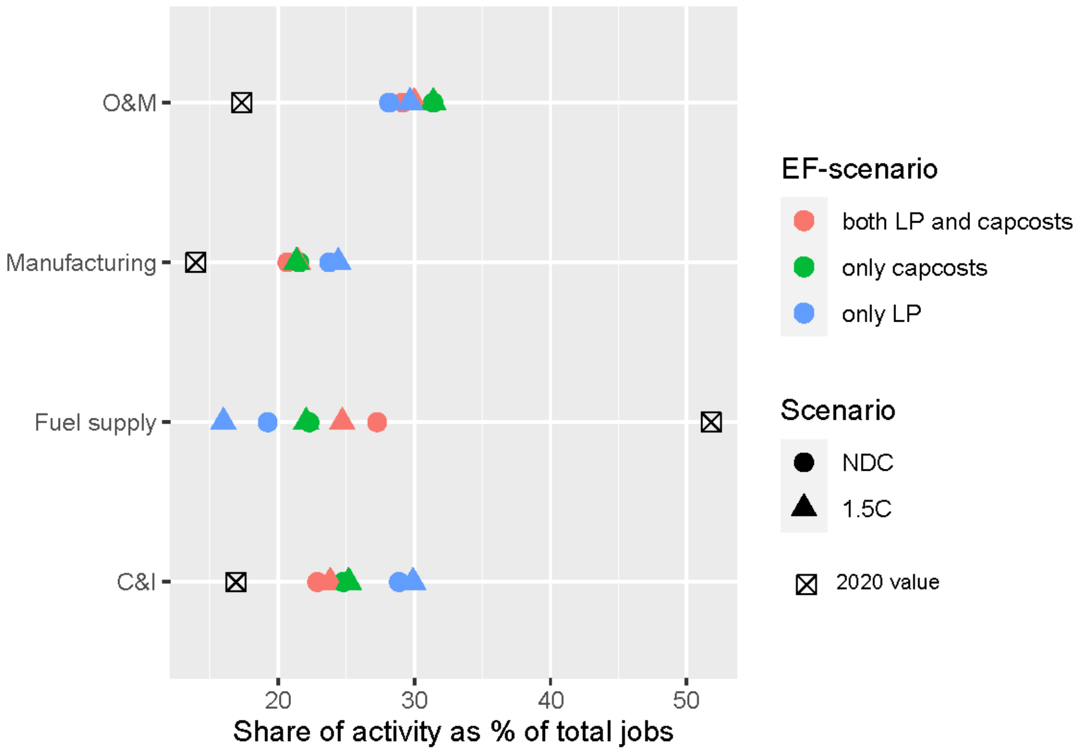


Figure S19 Share of activity in percent of total jobs, comparison between 2020 (boxed cross) and 2050

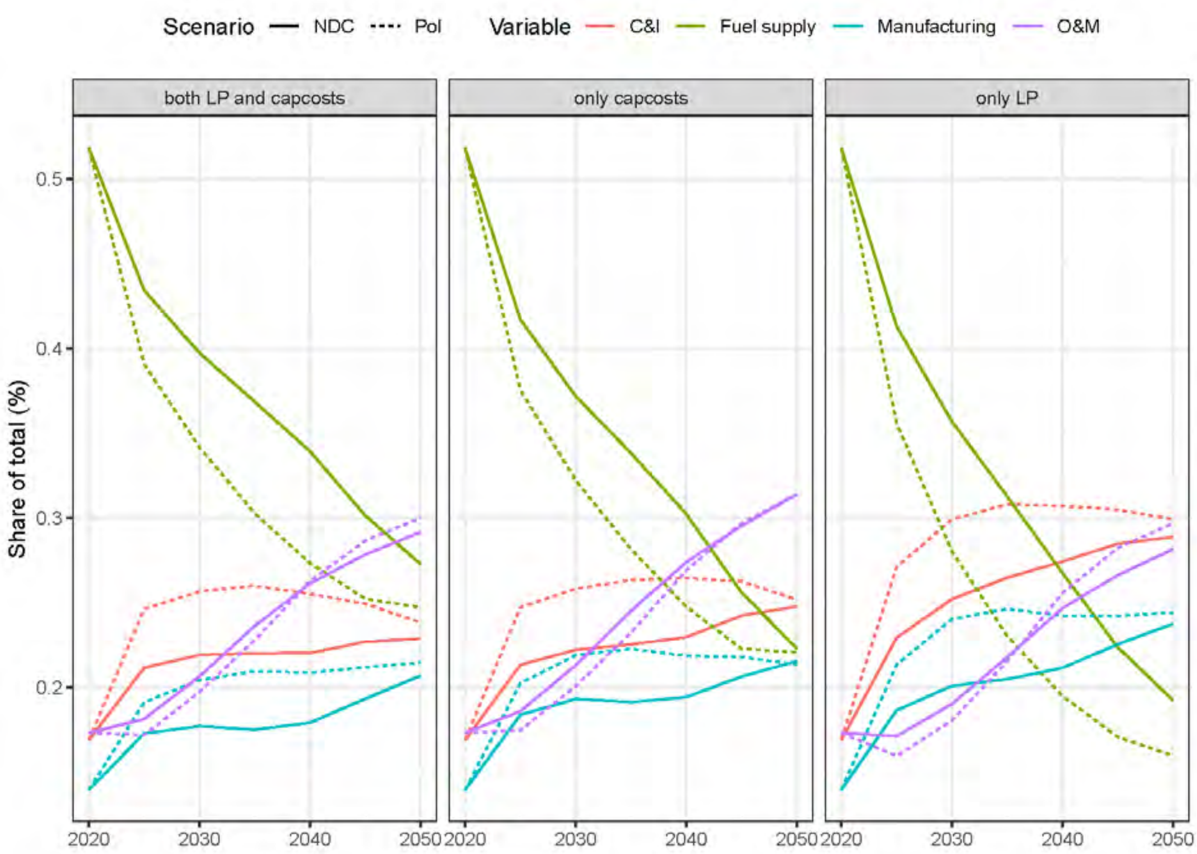


Figure S20 Share of activity in total jobs for different scenarios and EF-scenarios

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Chapter 4

Just transition opportunities for coal-bearing states in India[*]

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Christoph Bertram

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LETTER

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

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Keywords: energy, employment, india, just transition, coal states, political economy, integrated assessment model

Supplementary material for this article is available online

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

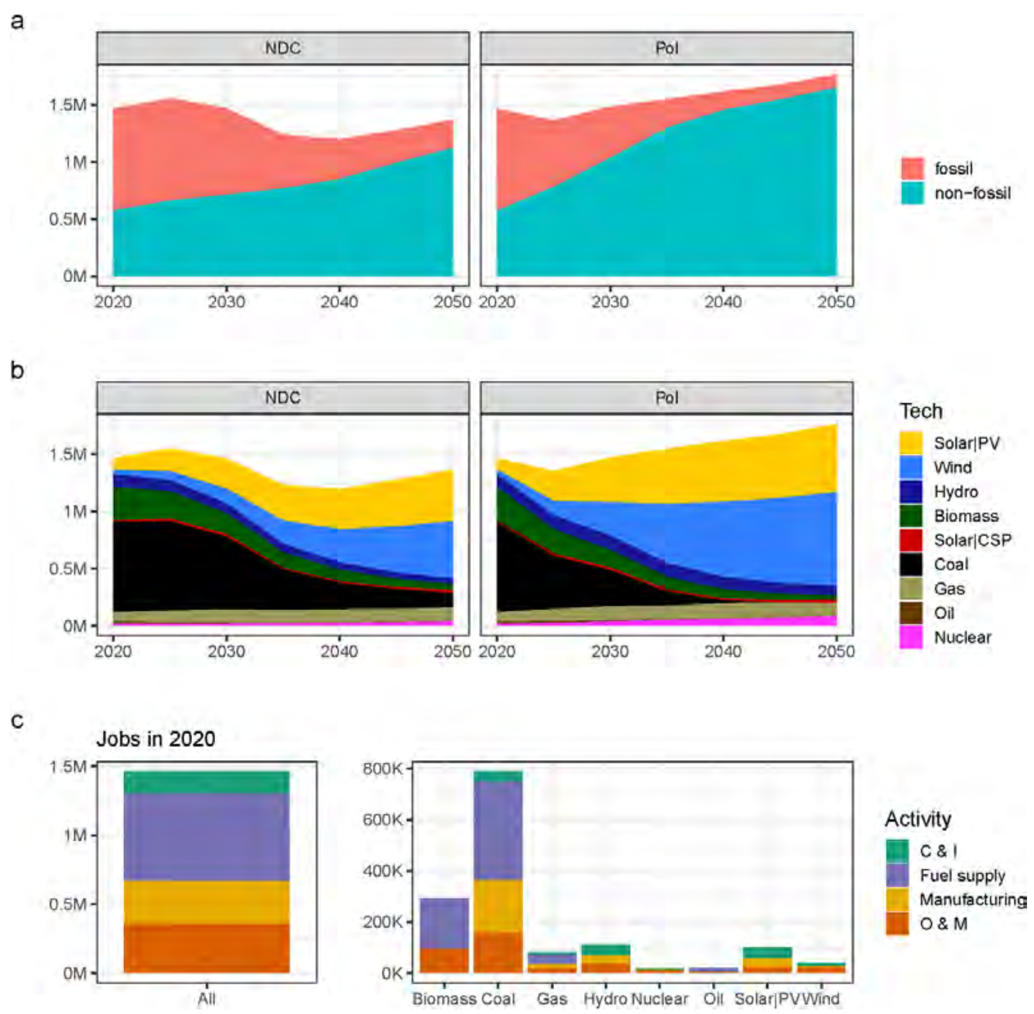

Figure 1. Total energy supply jobs in India by (a) scenario and type (b) by scenario and technology for NDC and 'Pol' (1.5 °C) policy cases, (c) energy jobs in 2020 by activity for different technologies.

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

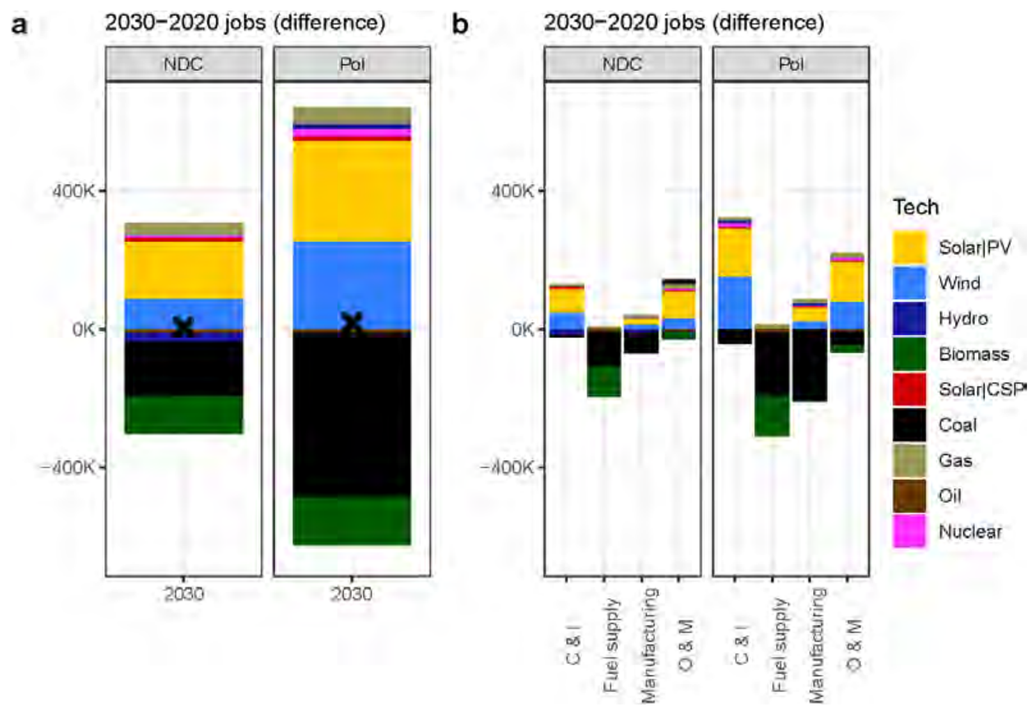

Figure 2. Changes in direct energy jobs from 2020 to 2030 for (a) different technologies (with the black cross denoting the net gain/loss) and (b) technologies and activities, for the two policy scenarios.

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).

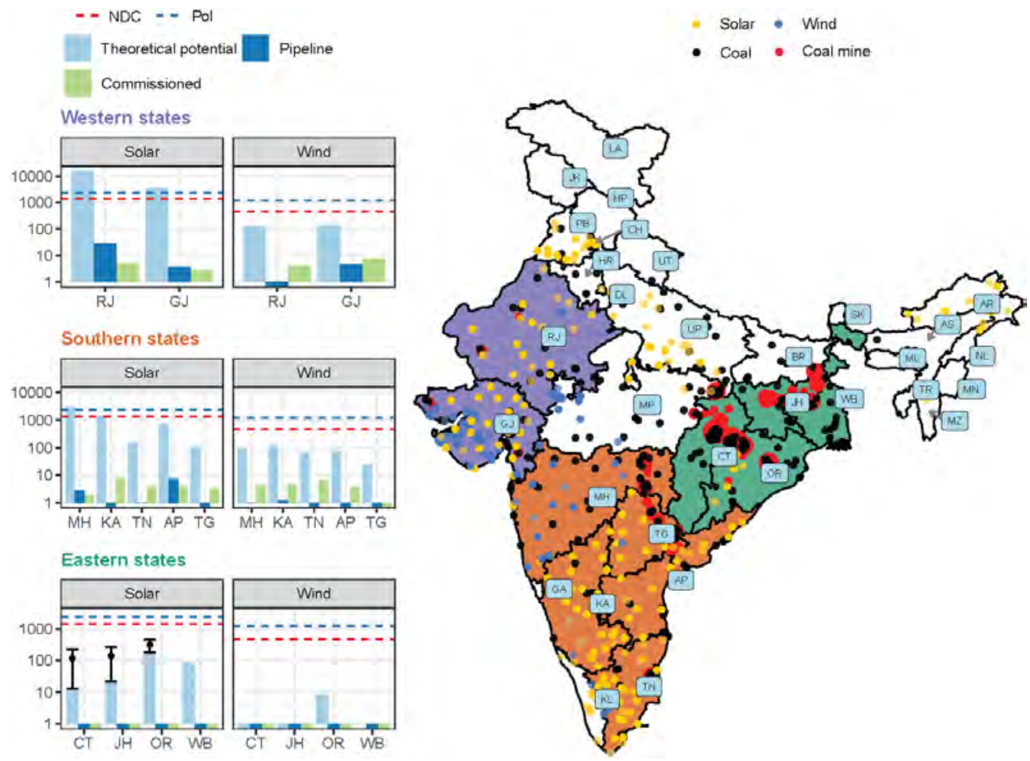

Figure 3. Left panels—solar and wind technical potentials (light blue), using a conservative estimate, commissioned (green) and pipeline (dark blue) power projects (all in GW) for the three 'state classifications': western, southern, and eastern states. For the eastern states of CT, JH, and OR, a range 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

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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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Supplementary information to “Solar energy as an early just transition opportunity for coal-bearing states in India”

1 Mapped capacity

The mapped capacity represents the capacity marked as data points in Figure 3 in the main text and Figure S1 below. The location and capacity data for the different technologies has been taken from different data sources – i) coal power plants and coal mines (operating and under-construction/planned) from the Global Energy Monitor 2021; ii) solar, wind, biopower and co-generation, small hydro power plants from Renewable Energy Project Monitoring Division 2020; iii) gas, oil, nuclear, and large hydro[1] from World Resources Institute et al. 2018.

Power plant locations in i) and iii) were available at unit/plant level and were generally exact. Other relevant notes are on corresponding webpages[2]. Power plant locations in ii) are generally accurate at a district level, however, data is generally of poor quality. The addresses available as part of the report were cleaned and then geocoded using Google Maps API, followed by again checking for inconsistencies. The result is that the mapped capacity is much lower than reported plant-wise capacity (Solar ~ 25 GW mapped vs. 29.9 GW reported, Wind 34.2 GW mapped vs. 37.4 GW reported)

State	Biopower	Co-gen	Coal	Gas	Hydro	Nuclear	Oil	Solar	Wind
Andhra Pradesh	489.81	0	12961	4671.284	3648.4	0	0	3987.78	4072.89
Arunachal Pradesh	0	0	0	0	411	0	0	3.68	0
Assam	0	0	750	610.45	375	0	0	0	0
Bihar	0	0	6400	0	20	0	0	0	0
Chandigarh	0	0	0	0	0	0	0	17.545	0
Chhattisgarh	0	0	26845	0	120	0	0	0	0
Dadra and Nagar Haveli and Daman and Diu	0	0	0	0	0	0	0	16.74	0

[1] The hydro column Table 1 represents sum of small hydro (<25 MW) and large hydro (>25 MW) taken from two different data sources.
[2] https://datasets.wri.org/dataset/globalpowerplantdatabase and https://globalenergymonitor.org/projects/global-coal-plant-tracker/

Delhi	0	0	0	2066	0	0	0	147.16	0
Goa	0	0	0	48	0	0	0	0	0
Gujarat	0	0	17355	7683.161	1995	440	0	2613.18	7237.45
Haryana	0	0	5980	431.586	62.4	0	0	0.13	0
Himachal Pradesh	0	0	0	0	10714.17	0	0	0	0
Jammu & Kashmir	0	0	0	0	2989.4	0	175	0	0
Jharkhand	0	0	5876.5	0	214	0	0	0	0
Karnataka	134.32	1731.61	9750	406.5	4580.21	880	106.6	5944.06	4778.67
Kerala	0	20	0	515	2080.09	0	177.84	91.53	51.88
Ladakh	0	0	0	0	96.75	0	0	0	0
Madhya Pradesh	0	0	22415	75	2319.1	0	0	265	515.4
Maharashtra	215	2485.7	26312	3489.88	3548.73	1400	1009.7	377.6	4782.13
Manipur	0	0	0	0	105	0	0	0	0
Meghalaya	0	0	0	0	333.2	0	0	0	0
Mizoram	0	0	0	0	60	0	0	2	0
Nagaland	0	0	0	0	75	0	0	0	0
Odisha	0	0	17799.5	0	2011.5	0	0	315	0
Puducherry	0	0	0	32.5	0	0	0	0	0
Punjab	0	0	5680	0	1187.65	0	0	768.95	0
Rajasthan	114.3	0	11025	1054.83	440.86	1180	0	3772.55	4296.56
Sikkim	0	0	0	0	2177	0	0	0	0
Tamil Nadu	986	0	14226	1018.18	2236.7	2440	411.7	2295.27	8378.73
Telangana	216.6	0	7756.5	0	657.61	0	0	3497.47	126
Tripura	0	0	0	1103.1	15	0	0	0	0
Uttar Pradesh	1905.11	0	23357.7	1468.4	471	440	0	849.12	0

Uttarakhand	0	0	43	225	3656.75	0	0	0	0
West Bengal	0	0	14715	0	1372.7	0	0	0	0
Total	**4061.14**	**4237.31**	**229247.2**	**24898.87**	**47974.22**	**6780**	**1880.84**	**24964.77**	**34239.71**

Table S1 Capacity mapped in Figure 1 of main text.

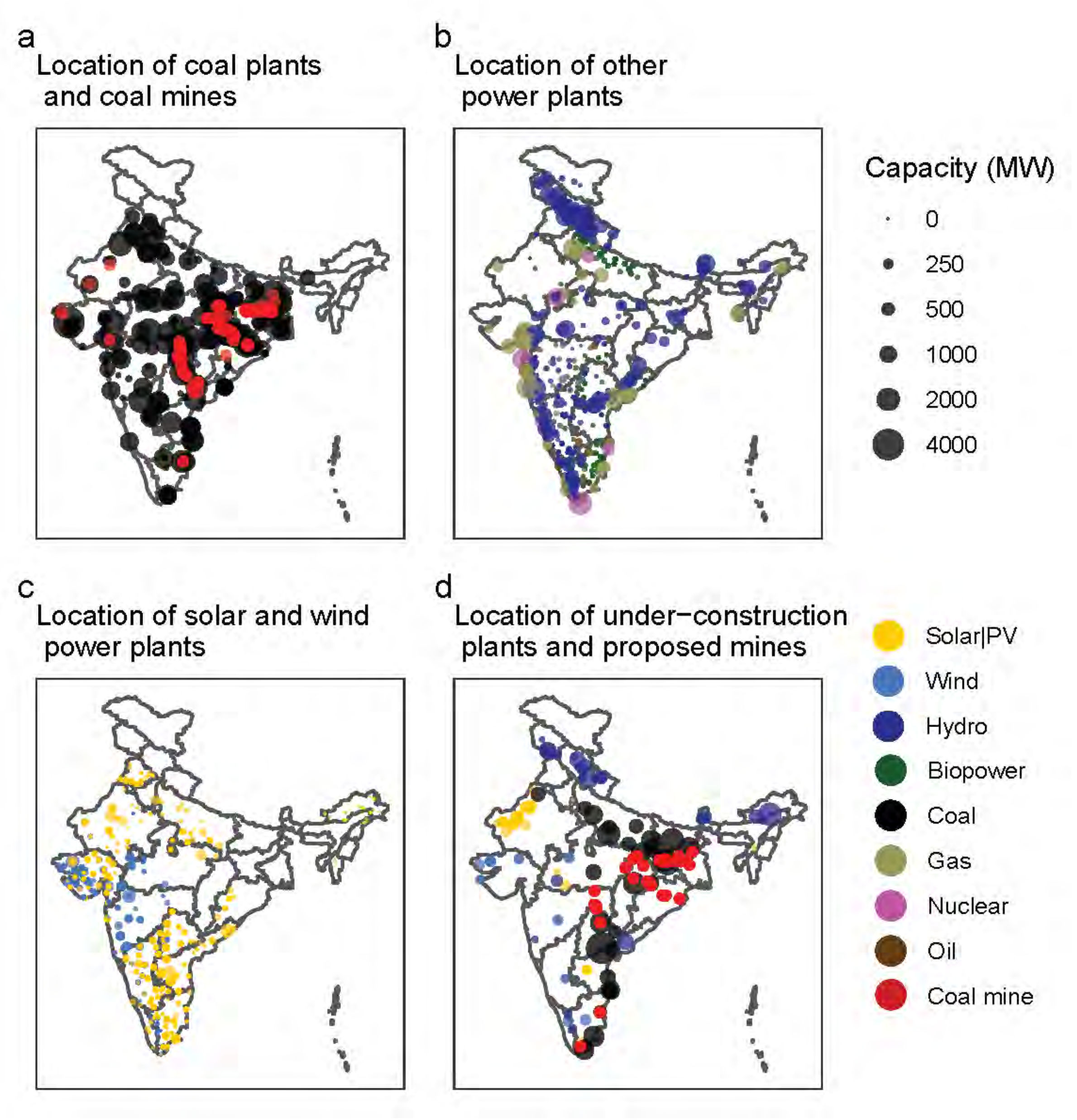


Figure S1 Location of power plants and mines in India, compiled from various sources - a) coal power plants in black, mines in red, b) Location of other power plants – gas, hydro, nuclear and oil c) location of solar and wind power plants, d) location of under-construction power plants – solar, wind, and coal, and proposed coal *mines (red). Note that i) for conventional power plants, capacity represents plant-level capacity (sum of units). For solar and wind, this may or may not be the case, ii) location of solar and wind plant data is approximate. Solar implies only Solar PV.*

2 Commissioned and pipeline capacity

Bridge to India's RE Navigator (https://india-re-navigator.com/utility) contains aggregate up-to-date information on state-wise, commissioned and pipeline installations. However, locational data is unavailable. Table S2 contains data for selected states. Note that solar only includes solar PV utility, i.e., excludes solar rooftop. Wind is wind onshore.

State	Type	Commissioned (GW)	Pipeline (GW)	Total (GW)
Rajasthan	Solar	5.1	27.5	32.6
Rajasthan	Wind	4.1	0.4	4.5
Gujarat	Solar	2.6	3.9	6.5
Gujarat	Wind	7.8	4.8	12.6
Andhra Pradesh	Solar	4	7.5	11.5
Andhra Pradesh	Wind	3.8	0	3.8
Karnataka	Solar	7.6	0.5	8.1
Karnataka	Wind	4.8	1.2	6
Tamil Nadu	Solar	3.9	1	4.9
Tamil Nadu	Wind	6.5	0.4	6.9
Maharashtra	Solar	1.9	2.9	4.8
Maharashtra	Wind	4.4	1	5.4
Madhya Pradesh	Solar	2.4	0.3	2.7
Madhya Pradesh	Wind	2.6	0.6	3.2
Odisha	Solar	0.4	0	0.4
Chhattisgarh	Solar	0.2	0	0.2
Jharkhand	Solar	0	0.1	0.1
Odisha	Wind	0	0	0
Chhattisgarh	Wind	0	0	0
Jharkhand	Wind	0	0	0
Telangana	Solar	3.5	0.2	3.7
Telangana	Wind	0.3	0	0.3
West Bengal	Solar	0.1	0	0.1
West Bengal	Wind	0	0	0

Table S2 Capacity Commissioned and in pipeline for different states from Bridge to Solar (update 15 March 2021)

3 Calculation of solar and wind technical potential

Solar potentials were calculated using the NREL RE-Data Explorer (https://www.re-explorer.org/re-data-explorer/technical-potential), using parameters in the **High constraint** scenario, see Table S3. The resulting potentials (Table S4 and resulting map, see Figure S2-left panel) should be considered conservative, as the allowed land use types were restricted to “wastelands” and “shrublands”. In comparison, the government authorised report on *India’s Wind Potential Atlas at 120m agl* from the National Institute of Wind Energy (NIWE) allows for much broader land-use types (next paragraph). Furthermore, soon to be commissioned floating-solar in India[3] shows the versatility of solar PV installations.

Only for eastern states of Chhattisgarh, Jharkhand, and Odisha, sensitivity analysis for other constraints (Medium and Low, see Table S3) were performed; results are in Table S5.

Wind technical potentials were taken from NIWE at 120m height (National Institute of Wind Energy, 2019) with the following parameters/constraints – i) Power density of 5 MW/km^2 , ii) Excluded areas - roads, railways, protected areas, airports; land area with elevation more than 1500m; land with slope more than 20 degrees, iii) capacity utilisation factor (CUF) more than 25%, iv) Suitable land areas – Waste land (80%)[4], Cultivable land (30%), Forest land (5%). See Figure S2, right panel for resulting map of suitable areas with CUF.

Criteria	High Constraint	Medium Constraint	Low constraint
Resource Type	Solar	Solar	Solar
Technology Type	Fixed tilt PV system	Fixed tilt PV system	Fixed tilt PV system
Limit by Solar Resource (kWh/m^2/day):	Min 4 Max 9	Min 4 Max 9	Min 4 Max 9
Power Density (MW/km^2):	100	100	100
Limit by Distance to Roads:	None	None	None
Limit by Distance to Transmission:	None	None	None
Exclude Protected Areas	Yes	Yes	Yes

[3] https://www.hindustantimes.com/india-news/indias-largest-floating-solar-power-plant-to-be-commissioned-by-ntpc-in-may-101615410322573.html
[4] Waste land includes grassland, other waste land, scrubland, and Rann (National Institute of Wind Energy, 2019).

Exclude Land Use Types:	All except – • Barren or Sparsely Vegetated • Shrubland	All except – • Barren or Sparsely Vegetated • Shrubland • **Dryland Cropland/Pasture (5%)**	All except – • Barren or Sparsely Vegetated • Shrubland • **Dryland Cropland/Pasture (10%)**
Limit by slope (%):	Max 5	Max 5	Max 5

Table S3 Criterion and constraints used to calculate solar technical potential using NREL's RE-Data explorer tool. The differentiating assumptions are highlighted in bold.

State	**Code**	**Solar technical potential (GW)**[5]	**Wind technical potential (GW)**	**Weighted average solar capacity factor for suitable areas in high constraint scenario**
Rajasthan	RJ	15179	128	0.182
Gujarat	GJ	3469	143	0.181
Madhya Pradesh	MP	108	15	0.176
Maharashtra	MH	3114	98	0.180
Karnataka	KN	1486	124	0.180
Tamil Nadu	TN	148	69	0.179
Andhra Pradesh	AP	718	75	0.180
Telangana	TG	111	25	0.177
Odisha	OR	182	8	0.166
Jharkhand	JH	22	0	0.168
Chhattisgarh	CT	13	0	0.172
West Bengal	WB	85	1	0.162

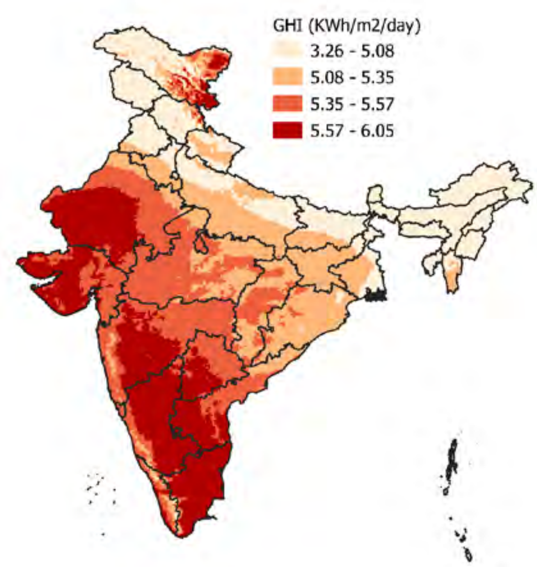
Table S4 Solar and Wind technical potential (in GW) for selected states in India, along with potential weighted capacity factors. Solar potential and capacity factors from NREL's technical potential tool (for high constraint), while wind potentials are from the National Institute of Wind Energy 2019.

[5] Potential considers only solar utility.

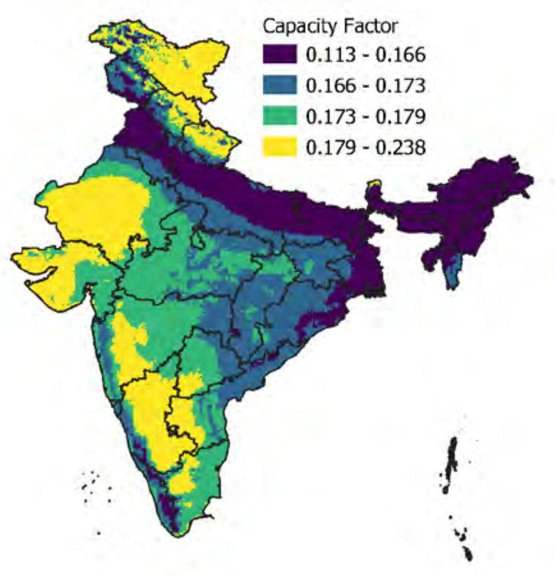
State	Solar potential (GW)		
	High constraint	**Medium constraint**	**Low constraint**
Chhattisgarh	13	115	218
Jharkhand	22	141	260
Odisha	182	313	445

Table S5 Potentials for utility scale solar for various assumptions on land constraints for the eastern states of Chhattisgarh, Jharkhand, and Odisha

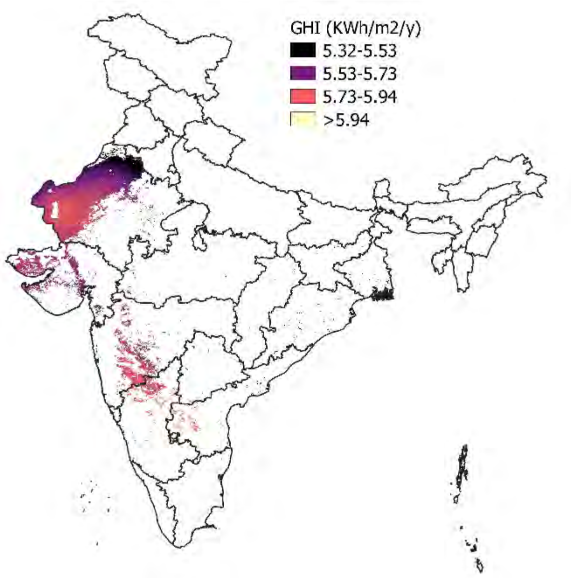
(a)



(b)



(c)



(d)

Figure S2 a) All-India Global Horizontal Irradiance (GHI) (Kwh/m2/day) b) All-India capacity factor for solar c) Map showing GHI for suitable areas in the high constraint scenario from NREL d) Wind potential according to Capacity Utilisation Factor (CUF) for India from National Institute of Wind Energy 2019 (For original figure see Figure 9 in report. The figure has not been included for copyright reasons). All maps (a-c) produced on QGIS with data from NREL's RE-data explorer.

4 Manufacturing locations of solar components

Item	Company	Location (Town/city)	State	Capacity/ yr	Status
module and cell production	Adani solar	Mundra Special Economic Zone	Gujarat	1.5 GW	operating
module production	Emvee	Bangalore	Karnataka	500 MW	operating
module production	Gautam solar	Haridwar	Uttar Pradesh	250 MW	operating
module production	Goldisolar	Surat	Gujarat	500 MW	operating
module production	Insolation Energy (INA)	Jaipur	Rajasthan	200 MW	operating
module production	Premier Energies	Hyderabad	Andhra Pradesh	500 MW	operating
module and cell production	Premier Energies	Hyderabad	Telengana	1.5 GW	operating
module production	Rayzon solar	---	Gujarat	300 MW	operating
module production	RenewSys	Patalganga	Mahashtra	750 MW	operating
module production	Saatvik	Ambala	Haryana	500 MW	operating
cell production	Tata Power Solar	Bengaluru	Karnataka	530 MW	operating
module production	Tata Power Solar	Bengaluru	Karnataka	580 MW	operating
module production	Vikram	Indospace Industrial Park, Oragadam	Tamil Nadu	1.3 GW	operating
module production	Vikram	Falta	West Bengal	1.2 GW	operating
module production	Waaree	Tomb	Gujarat	1 GW	operating
module production	Waaree	Surat	Gujarat	1 GW	operating

module and cell production	Adani solar	Mundra Special Economic Zone	Gujarat	2 GW	Planned/under-construction
module production	Emvee	Dobaspet	Karnataka	3 GW	Planned/under-construction
module production	First Solar	---	Tamil Nadu	3.3 GW	Planned/under-construction
module production	Goldisolar	Navsari	Gujarat	2 GW	Planned/under-construction
module production	Insolation Energy (INA)	Jaipur	Rajasthan	500 MW	Planned/under-construction
module production	Jakson Group	Noida	Uttar Pradesh	500 MW	Planned/under-construction
module and cell production	Premier Energies	---	---	1 GW (cell) + 1 GW (module)	Planned/under-construction
module production	Rayzon solar	---	---	1.2 GW	Planned/under-construction
module production	RenewSys	Dholera Special Industrial Region	Gujarat	2 GW	Planned/under-construction
module production	Solex	Surat	Gujarat	1 GW	Planned/under-construction

Table S6 Location of operating and under-construction/planned solar PV manufacturing plants in India. Gathered from various sources.

5 Evolution of capacity, production, and new capacity in REMIND scenarios

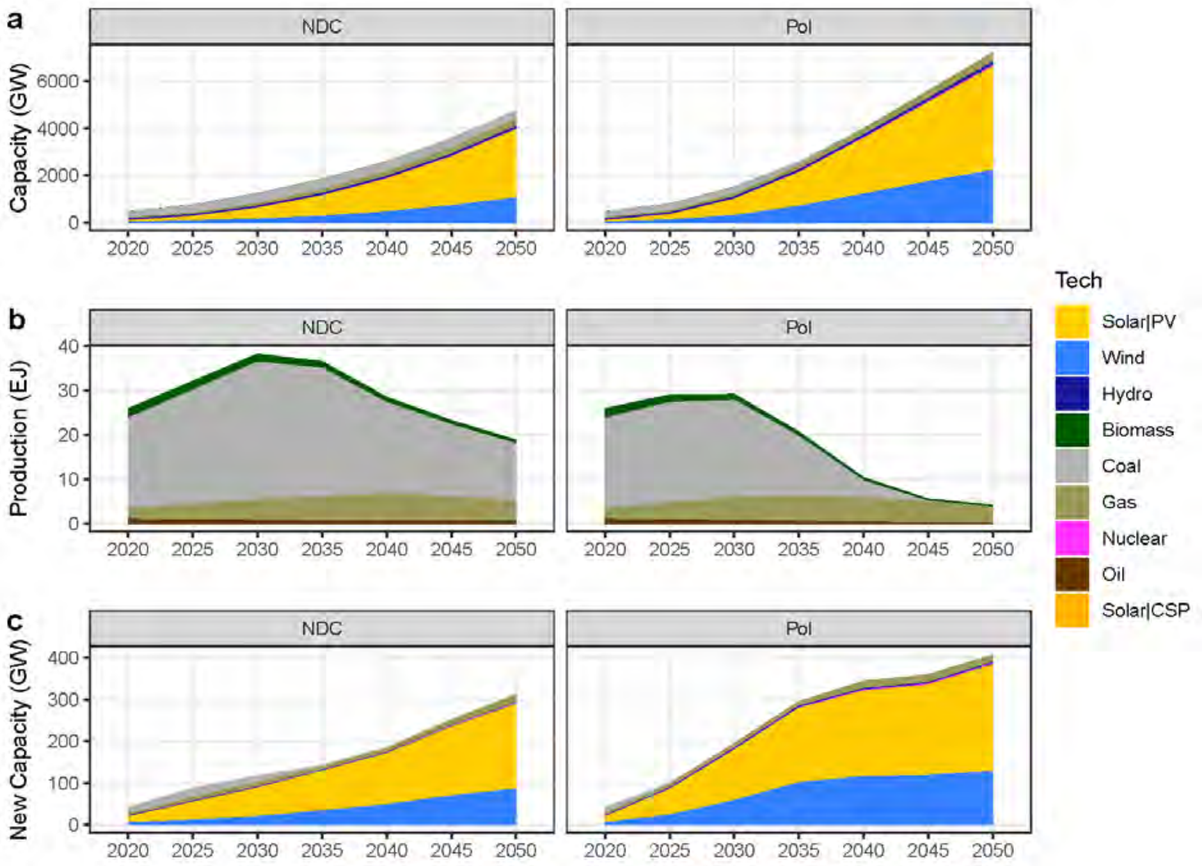


Figure S3 Capacity (GW), Production (EJ) and New Capacity (GW) for different technologies, for the two policy scenarios - NDC and Pol (1.5C-compatible)

6 Replacing coal mining jobs with solar jobs

Year	Average Employment factor – solar utility (EF_{SU}) (FTE/MW)		Average Employment factor – solar rooftop (EF_{SR})(FTE/MW)	
	O & M	**C & I**	**O & M**	**C & I**
2020-2025	0.4	1.8	0.4	4.88
2025-2030	0.25	1.25	0.25	3.2

Table S7 Average employment factor for the different time steps for solar utility and rooftop, for the two activities – O & M and C & I.

Calculation for Case I: Coal jobs only replaced by O & M jobs in solar-utility

In this case the solar capacity required to replace coal mining jobs during that particular year is:

$$Solar\ capacity\ required = Coal\ jobs\ lost/Employment\ factor_{\ O\ \&\ M}$$

This calculation is identical for both time steps.

Calculation for Case II: Coal jobs replaced by both O & M and C & I jobs in both solar utility and solar rooftop (20% of total)

Unlike operation and maintenance (O & M) jobs which are created for the lifetime of a power plant, construction and installation (C & I) jobs are concentrated for a limited time at the start of a power project; e.g., solar PV-utility the average is approximately 1 year. However, in an economy, where many projects are being built (and replaced) every year, people employed in C & I could in principal, continue having jobs much longer than the initial period. To consider C & I jobs as long-term jobs, we assume: i) that in 5-yr time step, the total C & I jobs resulting from the installed solar capacity are divided by 5, because assuming constant yearly installations the same number of people are employed during each of those years; ii) in the next time step, people from the previous time step need to be re-employed, however because of the decreasing employment factor / increasing labour productivity, higher capacity needs to be installed for a given amount of jobs.

For the first time step (2020-2025), the required solar capacity to replace coal jobs is:

Total solar capacity to be added/replace coal jobs= x

Of that, solar utility is assumed to provide 80%, and solar rooftop 20%

Coal jobs to be replaced = y

Coal jobs to be replaced = Jobs in O & M solar utility + Jobs in O & M solar rooftop + Jobs in C & I solar utility + Jobs in C & I solar rooftop

$$y = EF_{O\&M\_SU} * (0.8x) + EF_{O\&M\_SR} * (0.2x) + \left(EF_{C\&I\_SU} * (0.8x)\right)/5 + \left(EF_{C\&I\_SR}(0.2x)\right)/5$$

$$x = y/\left[EF_{O\&M\_SU} * (0.8) + EF_{O\&M\_SR} * (0.2) + \left(EF_{C\&I\_SU} * (0.8)\right)/5 + \left(EF_{C\&I\_SR}(0.2)\right)/5\right]$$

Note that the employment factors correspond to those of 2020-2025; see Table S7.

For the second time step (2025-2030), the required solar capacity is:

In this time step, people in C & I from the last time step need to be re-employed in the same sector. This requires a certain capacity addition:

Total solar capacity to be added = X

Of that, solar utility is assumed to provide 80%, and solar rooftop 20%

People in C & I from last time step = Z

$$X = 5 * Z/ \left(EF_{C\&I\_SU} * (0.8)\right) + \left(EF_{C\&I\_SR} * (0.2)\right)$$

Note that the employment factors correspond to those of 2025-2030; see Table 8.

Additionally, the installation of X creates long-term jobs in O & M (W):

$$W = X* \left(EF_{O\&M\_SR} * (0.2) + EF_{C\&I\_SU} * (0.8)\right)$$

Thereby reducing the number of coal jobs to be replaced in the time step:

Jobs to be replaced = Coal jobs lost in the time step – W

Jobs to be replaced = y_2

Solar capacity to be added/replace coal jobs: x_2

Jobs to be replaced = Jobs in O & M solar utility + Jobs in O & M solar rooftop +

Jobs in C & I solar utility + Jobs in C & I solar rooftop

$$y_2 = EF_{O\&M\_SU} * (0.8x_2) + EF_{O\&M\_SR} * (0.2x_2) + \left(EF_{C\&I\_SU} * (0.8x_2)\right)/5 + \left(EF_{C\&I\_SR}(0.2x_2)\right)/5$$

Total solar capacity to be installed in the time step: X + x_2

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Chapter 5

Synthesis and Outlook

5.1 Summary of chapters

The three studies presented in the preceding chapters examine the different challenges to decarbonisation in India. A summary of the chapters is provided in the subsequent sections.

Chapter 2: Reducing stranded assets through early action in the Indian power sector

The second chapter reveals that early climate action in the Indian power sector greatly reduces the risk of stranded assets under the Paris Agreement regime. Even assuming anticipated reductions in solar PV, wind, and battery costs, and current RE targets, model projections show that India continues to build coal power plants until 2030. In pathways where mitigation starts thereafter, to limit warming to well-below 2 °C, almost half of this yet-to-be-built capacity gets stranded. If stringent climate mitigation is to start immediately, the stranding is lower, however this entails massive build up of RE and high carbon prices.

A more politically feasible pathway in the near-term and an intermediate between the two policy scenarios, current policies and the 2 °C consistent scenario, could be a 'coal moratorium', where no power plants beyond those under construction are allowed and existing plants run until the end of their lifetime. Such a policy could have additional benefits — e.g., 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 the important groundwork for ambitious future climate policy.

Chapter 3: Climate policy accelerates structural changes in energy employment

The third chapter uses the employment factor approach to estimate the number and structure of global jobs in the energy supply sector for two scenarios: NDC and 1.5 °C-compatible. In the near-term, net gains are seen only in the 1.5 °C policy case, despite relatively higher losses in the coal mining sector. For both these scenarios, the direct energy supply jobs decrease in the future (2050) compared to 2020, driven by improvements in labour productivity. However, higher climate policy ambition leads to higher employment. Lastly, the increase in cumulative solar and wind capacity, against the decrease in total fuel production, means that the O & M jobs overtake fuel supply as the major share of total jobs in the future.

Despite the higher gains in jobs in the policy scenario, the regional picture could look very different. The extent to which employment considerations could affect the pace of decarbonisation depends on regional and skill-related factors e.g., size of the power sector, the overlap between regions of coal mines and RE-rich areas, skill-overlap between fossil and RE-jobs and other policies in place, e.g., encouraging local manufacturing, increasing investment in coal-related communities to help with the transition, etc.

Chapter 4: Solar energy as an early just transition opportunity for coal-bearing states in India

The fourth chapter argues that just transition needs to be adequately addressed in India's energy transition and that solar could play a limited but important role in bringing about the just transition. In India, both existing and planned solar and wind plants are concentrated in the south and western parts of India and overlap largely with areas of high resource potentials. On the other hand, fossil fuel infrastructure — mainly coal mines and without power plants are located in the eastern states and would house future under-construction/planned fossil infrastructure. We show that the pathways based on current policies would create a sharp regional divide in future energy infrastructure and associated jobs. This would become even larger in decarbonisation scenarios, as it leads to higher jobs losses in coal mining in the eastern states but significant increases in jobs along the renewable value chain in the southern and western states. Without specific policies addressing this mismatch, the road towards decarbonisation could face political push back. Substituting all lost coal jobs with long-term jobs in solar energy would be extremely difficult as it would require a significant share of future all-India solar capacity additions to go to a few coal states.

At the same time dedicated policies to ensure early geographic diversification of solar locations 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 local health.

5.2 Discussion and Policy implications

In chapter 2 we identified that an early move to stringent mitigation policies in India, for example a coal moratorium, could lessen the risk of future stranded assets of coal power plants. These plants, with their long life times create path-dependence, thereby affecting the future evolution of the power system. India should instead aim to further increase its renewable energy ambition. This might lead to near-term increase in price of electricity, however over a longer period proves to be cheaper than a fossil-dominant system (Lu et al., 2020). Moreover, given the extremely dynamic nature of the current world renewable energy system with its steadily decreasing capital costs, India would do well not to lock into a system of coal power. There are now some indications that a moratorium on building no new coal power might emerge from existing circumstances in the power sector. The states of Gujarat, Chhattisgarh, and Karnataka announced no new construction of coal power plants (Carbon Copy, 2019). National Thermal Power Corporation, India's largest coal-power generator, also announced that it will not pursue any new greenfield development of coal-fired power projects and plans to have 45% of its installed capacity from RE by 2032 (IANS, 2020). Furthermore, no new Indian coal-fired power plants were announced in 2019–2020 and there has been no progress on the 29.3 GW of pre-construction (includes announced, pre-permitted, and permitted plants) project pipeline during this time (Global Energy Monitor, 2021). While the private sector is moving away from coal power, new plans and announcements mainly come from central and state government companies, financed primarily using central government funds (Shah, 2021).

Although ambitious near-term policies for renewable energy and a moratorium on coal might have advantages as described above, they will shift the distribution of energy infrastructure and associated employment, as analysed in chapter 3. For example, energy investment and jobs will shift away from regions with fossil resources to manufacturing centers of wind and solar components and areas of high solar and wind potentials. In fact, one reason for the government of India's continued push on coal is that an immediate and quick transition to renewable energy would entail significant imports and loss of local jobs. Although commissioning and installations jobs are created locally, the majority of the manufacturing of solar cells and panels takes place outside India. In 2018, domestic manufacturers had a market share of 7% (Singh, 2018) in solar cells, with the majority of the imports from China [1], implying that India would have to pay significant

[1] India fares much better in manufacture of wind energy components, with almost 70-80% indigenisation (Ministry of New and Renewable Energy, 2021)

foreign exchange and transform from a mainly in-house manufacture, construction, and production of coal and coal power, to an import-based RE energy sector. India already depends significantly on imports for oil and gas, 75% and 50% respectively in 2019 (IEA, 2021); coal with its large reserves, and coal power with an established legacy are seen as symbols of reliability, efficiency, and security (Montrone et al., 2021). Although local solar cell and module manufacture failed to grow in India in the past, outcompeted by its Chinese counterparts (IRENA, 2019), the government remains keen on developing an indigenous manufacturing base. After releasing tenders with locally manufactured components failed, it has recently brought up a production-linked incentive scheme to bolster domestic manufacture (of both panels and batteries) and deterred imports by increasing the customs duty on imported panels (Carbon Copy, 2021b,c,a). Although domestic manufacture would create local jobs, they would possibly increase capital costs of solar, at least in the near-term. It remains to be seen how this would affect India's solar ambitions and in turn the pace of decarbonisation, and if the scheme proves to be more successful than its predecessors.

Chapter 4 begins with the premise that decarbonisation, both near and long-term, could be hindered if losers from the transition, be it states, firms, and the people employed are not adequately compensated or provided with alternate opportunities. In other words, an energy transition as mentioned in chapter 2 might be feasible from a techno-economic point of view but might be politically infeasible. Chapter 4 therefore explores this feasibility by examining the current and future course of energy infrastructure and energy jobs concentration in India. In contrast to chapter 3, where the focus is global and across countries, this chapter focuses on states within the country. The eastern states of Chhattisgarh, Odisha, and Jharkhand produce almost 60% of coal in India, the mining bringing significant revenue for both the state and the central government. Although the people directly employed in coal mining are a very small fraction of the total workforce in these states, many people are informally employed in coal mining, and others indirectly or induced [2] employed through coal mining - e.g., employed in temporary construction works in mining premises, truckers transporting mined coal and overburden, as staff in hospitals and schools run by coal companies, or in hotels and restaurants around coal mines (Bhushan et al., 2020) [3]. Coal mining also provides jobs in allied sectors, such as coal washeries. On the other hand, the wealthier western and southern states of India are projected to gain most of the energy transition, mainly due to high resource potentials in these states. Thus, without adequate compensation or work opportunities to replace coal, people could oppose the transition. In fact, according to Bhushan et al. (2020), one

[2] induced jobs are created through consumption of goods and services of people employed directly or indirectly with an industry or sector

[3] this effect, however, maybe be hyper-local and the dependence of coal on total income fades with distance (Bhushan et al., 2020).

reason why centre-controlled Coal India Limited continues to run so many small-scale unprofitable mines is because of the pressure of workers' unions.

5.2.1 Future international climate action

The three core chapters in this thesis have been primarily addressed to local governments, identifying barriers to decarbonisation and solutions how to overcome them. However, as mentioned in the introductory chapter, national action on climate is heavily influenced by action of other countries and agreements in international negotiations. Developing countries, especially India, have iterated consistently for decades that energy justice considerations ('common but differentiated responsibility') need to be recognized by developed nations so as not to stifle its development and that its climate commitments should not be seen under the same umbrella as theirs. It is clear that if achieving the Paris Agreement requires carbon neutrality by 2050, then based on differentiated responsibility, either richer nations need to take on more emission reductions or provide financial and technological support to developing countries to scale up their renewable capacity. However, so far developed nations have even fell short of the commitment of $100 billion dollars a year by 2020 of climate finance. The COP 26 in Glasgow should therefore focus not only on increased mitigation effort of richer nations 'at home' but action on providing cheap finance and technological know-how, for example of manufacturing of renewable energy components, to support developing countries build new renewable energy plants instead of new coal power plants and get locked into coal.

5.3 Limitations

Although the thesis uses a conceptual framework to investigate the barriers in power sector decarbonisation, the papers in this work do not cover every aspect of the framework. The second and third chapters cover the impact of mitigation scenarios on employment but they miss on other indicators affecting the political and institutional constraints of these scenarios. Chapter 2, for example, assumes that carbon pricing becomes immediately available in an economy and that the price could be set to be very high within a span of a few years. Experience from other countries has shown that a properly functioning carbon market, encompassing multiple sectors can take years and is often preceded by a long term of technology-specific targets and policies toward decarbonisation. The chapter also does not consider the distributional implications of applying a carbon revenue evenly across all polluting sectors. Here too, studies reveal that both the level of carbon price and how the revenue is used by the governments plays an important role in people's acceptance of mitigation measures. The chapter also assumes that competition between various technologies producing electricity happens on the power market. In reality, power distribution companies are often limited in their options due to long-term contracts with generators. Some of them even specify the payment of fixed charges even if no electricity is purchased, thus facing different prices compared to the wholesale price. Lastly, although most energy models include some representation of the rate of renewable capacity expansion in the near-term, for example through additional markup costs, these might not capture the full range of country-specific barriers in accessing finance and the risk of investments. In India, state-run distribution companies are under constant financial losses and owe billions of dollars to generators; in turn affecting the latter's investment returns.

Chapter 3 and chapter 4 focus on the employment implications of mitigation scenarios of different stringency, thereby assessing how changes in employment of various technologies and stages of production could impact the pace of decarbonisation and what could be possible solutions to overcome these barriers. Due to the limitations of the methodology, we cannot comment on how the scenarios would impact people employed indirectly in the power sector or employed informally. These factors could become very important in areas immediate to where a resource is located. Chapter 4 also does not discuss on the political impact of the energy transition through the sectors affiliated to coal extraction. Coal accounts for almost half of both the total freight and the total freight revenue for the railways (Kamboj and Tongia, 2018; IEA, 2021), and 60% of the total coal consumed by the power plants is transported through rail. Train freight charges in India are some of the highest in the world, particularly because they in turn subsidise passenger transport.

5.4 Suggestions for future research

Future research in context of the research theme should be directed into addressing the various limitations described in the last section. Firstly, pathways of energy transition, especially for low-income countries with high development priorities, need to provide a more holistic picture of the implications of the transition, so that the discussion is not reduced to one single parameter like the 'cost of electricity' or 'carbon price'. This means getting better at integrating key environmental externalities like air pollution but also social implications like inequality, hunger, distributional impacts, etc. which affect the political feasibility of mitigation scenarios. At the same time, care should be taken while extending energy and climate-energy models to beyond what they were originally conceived, for example, by encouraging multiple methods, approaches, and model intercomparison exercises. Secondly, to increase the confidence of using the employment-factor approach for employment estimation, long-term empirical studies should be carried out on finding the employment factor along the value chain, especially in non-OECD countries, where data is currently scarce. Lastly, for the just transition of coal workers and communities in India, research should investigate opportunities beyond the energy sector.

5.5 Conclusion

Fulfilling the goals of the Paris Agreement requires that all nations collectively pursue deep decarbonisation. The starting point in this endeavour is the power sector. Even for low-income countries, with high development priorities and low historic responsibilities, there are strong reasons to start decarbonizing the power sector now. However, there are barriers to this process which go beyond techno-economics, into governance, and institutional and political factors. Investigating the nature of these factors is essential to decarbonise quickly and effectively. In the preceding chapters we identified some of these barriers and proposed solutions how to overcome them. In chapter 2, the barriers took the form of stranded assets which could be overcome through increased near-term investments in renewable and a moratorium on construction of new coal plants. In chapter 3, the barriers were structural changes to energy employment, specifically the losses in coal mining, which however could be reduced through job-transfer in the renewable energy sector, provided that retraining efforts are successful. In chapter 4, the barriers became more nuanced as we compared how energy infrastructure would evolve regionally across India and found that solar could play a small but important role in the just transition of coal-bearing states.

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Statement of contributions

The core chapters of the dissertation (Chapters 2, 3, and 4) are published or submitted research articles, produced through the collaboration with colleagues both inside and outside PIK. The thesis author is the first author of all these articles, having contributed significantly to their conceptualisation, writing, and analyses. The author contributions for these chapters are as follows:

Chapter 2 - Both Aman Malik and Christoph Bertram conceptualised the study and the figures. Aman Malik wrote the manuscript and produced the figures. Elmar Kriegler and Gunnar Luderer provided feedback on the design and structure of the manuscript. All other authors provided scenario data for their respective models and gave feedback on the manuscript.

Chapter 3 - Aman Malik and Christoph Bertram designed the study. Aman Malik produced the figures and wrote the manuscript. Both Christoph Bertram and Aman Malik analysed the results. Both Elmar Kriegler and Gunnar Luderer provided inputs to the manuscript.

Chapter 4 - Aman Malik designed the study, produced and figures, and wrote the manuscript. Christoph Bertram gave valuable feedback in all stages of the manuscript.

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