Energy Strategy Reviews 49 (2023) 101152

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Assessing enhanced NDC and climate compatible development pathways for India

Saritha Sudharmma Vishwanathan [a,*], Panagiotis Fragkos [b], Konstantinos Fragkiadakis [b], Amit Garg [c]

[a] Social Systems Division, National Institute for Environmental Studies, Tsukuba, Japan
[b] E3Modelling S.A., Panormou 70-72, Athens, Greece
[c] Public Systems Group, Indian Institute of Management Ahmedabad, Gujarat, India

ARTICLE INFO

Keywords:
Enhanced NDC
Net zero
Integrated assessment modelling
Coal phase down
Climate compatible development pathway
India
Analysis paper

ABSTRACT

India has indicated a strong commitment towards mitigating climate change not only through its Nationally Determined Contribution (NDC) but also reiterating on raising its climate ambitions and committing towards Net Zero (NZ) in Glasgow. This study couples the bottom-up technology-rich energy system model with a macro-economic computable general equilibrium model to assess the socio-technical, financial and macro-economic implications of India's energy sector transformation away from coal. In order to move towards its NZ target by 2070, India will need to restructure its coal-based power and industry sector. This study provides insights on the challenges (stranded assets, loss of revenue) as well as the opportunities from energy sector restructuring (job creation, energy import reduction, improvement of local environment and human health).

1. Introduction

On November 2, 2021 at the Conference of the Parties (COP26) in Glasgow, Prime Minister Narendra Modi presented India's climate commitment and raised the ambition of its climate policy relative to the Nationally Determined Contribution (NDC) submitted during the Paris Agreement (COP21). This includes: (a) a further reduction of emission intensity of Indian GDP from 33 to 35% in its first NDC to 45% by 2030 based on 2005 level (existing target); (b) an increase in the share of non-fossil installed electric generation capacity from 40% to 50% (existing target); (c) to install 500 GW of non-fossil power generation capacity by 2030 (additional target); (d) to mitigate 1 billion tonnes of carbon dioxide equivalent (btCO_2e)[1] by 2030 (additional target); (e) the creation of a cumulative carbon sink of 2.5–3 btCO_2e through additional forest and tree cover by 2030 (ongoing target); (f) Indian Railways to become net zero by 2030 (additional target); and (g) to become a net-zero emissions economy by 2070 [1–4].

India is one of the key players in the international climate policy debate along with Europe, the United States of America, and China – aiming to achieve the Paris Agreement goals, while ensuring that citizens have access to affordable, secure, sustainable, low-emission energy to improve their socio-economic conditions. India's climate mitigation actions include a gradual moving away from coal in the future by terminating the construction of planned coal-based power plants has been projected in few of the states, in addition to the introduction of ambitious non-fossil fuel targets by 2030 [5,6]. After the Paris climate conference in 2015, India has raised its renewable generation capacity target from 100 GW by 2020 to 175 GW by 2022, and total non-fossil target to 450 GW by 2030. This ambition has been raised to 500 GW by 2030 at COP26 in Glasgow [2–4]. This has been complemented by sectoral policies, regulatory and market instruments to support and enhance the low-carbon transformation. However, coal is projected to remain the major fuel to fulfill India's energy security at affordable prices at least till 2030 under ongoing policies [5,7–10].

India has reduced its emission intensity of gross domestic product (GDP) by 24% between 2005 and 2016 [4]. According to current data estimates in 2019, India has achieved its 2020 Copenhagen Pledge (~27.7% reduction in carbon intensity of GDP over 2005–2019, excluding emissions from land use, land use change, and forestry (LULUCF)) and very close to meeting its Paris commitments on this goal (target 33–35% GHG/GDP over 2005 levels) almost a decade earlier. India should be noted that it is the only major country whose greenhouse

* Corresponding author. Social Systems Division, National Institute for Environmental Studies, Room 266, Tsukuba, Japan.
E-mail addresses: sarithasv@iima.ac.in, vishwanathan.saritha@nies.go.jp (S. Sudharmma Vishwanathan).

[1] cumulative between 2020 and 2030.

https://doi.org/10.1016/j.esr.2023.101152
Received 24 February 2022; Received in revised form 15 July 2023; Accepted 25 July 2023
Available online 3 August 2023

gas emission NDC pathways are consistent with a 2 °C compatible carbon budget [7,11–13]. The strengthening of Indian climate actions will contribute to the transition towards a well-below 2 °C and subsequently 1.5 °C world as set out in the Paris Agreement [7,9,10]. The current share of non-fossil fuels (including hydro) in installed power generation capacity is around 38% up from 29% in 2010, showing clear progress by India towards implementing this NDC target [14,15]. India, as of January 2022, has a total power generating capacity of 395 GW (GW), with 203.9 GW (~52%) of coal, 24.9 GW of natural gas, 46.5 GW of large hydro, 6.78 GW of nuclear, 40.1 GW of wind, 50.3 GW of solar, 10.1 GW of bio-power, and 4.8 GW of small hydro [15]. Coal-based generation was estimated to be around 1101 TWh in 2021, increasing with an average annual rate of 6.5% since 2002. Fossil fuels account for the majority of electricity generation, with their share standing at 81.2%, while hydro accounts for 11%, nuclear 2.5% and non-hydro renewable sources for about 4.8% [16].

India (after China) is the second largest producer, importer and consumer of coal and third largest power producer and consumer of electricity in the world (behind China and the USA); however, its electricity consumption per capita at 1208 kWh/capita is lower than other large emerging economies such as China, Brazil and South Africa [17]. Over 75% of power production is based on coal, which is the dominant domestic energy resource and thus provides energy security and affordability to a vast number of Indian households and businesses. Approximately 200 million people (~3% of households) still live without access to electricity. India will require more energy due to its rising population, urbanization and industrialization in addition to its myriad of development challenges in the coming decades [17,18]. Therefore, it is crucial for India: 1) to maintain its energy security, while achieving its NDC targets and the long-term goal of carbon neutrality by 2070, 2) to ensure access to affordable, clean and secure energy to all its citizens and businesses, 3) to create jobs for the current and future generation especially as more than 15million people are currently dependent on coal and associated businesses, and 4) develop alternative means of revenues for coal dependent states and coal associated businesses in order to ensure a just transition to a low-emission economy where no region, business or household is left behind.

The world is rapidly embracing decarbonization with large nations and businesses committing to meet the Paris Agreement Goals with a new wave of net zero pledges submitted in the last years both from developed and developing economies representing more than two thirds of global GDP [19]. India, a signatory to Copenhagen Accord (2009), Paris Agreement (2015), as well as the Glasgow Climate Pact (2021) will need to restructure its entire energy infrastructure to play a crucial role in achieving the Paris Agreement temperature goals. In order to move towards the net-zero target by 2070, India will need to restructure its coal use well before 2070. An important aspect of this transition involves the gradual reduction of coal demand across various sectors (most importantly in electricity production and industries) through numerous policy measures and regulations both by governments (federal, state, local) and businesses. The implementation of these actions will have severe transitions not only in the coal sector but also in the entire coal supply chain (which includes mining, transportation, distribution, use and ash disposal) in addition to international coal trade and will also have positive repercussions in non-fossil sectors of the Indian economy and energy system.

Previous studies have looked into India's energy transitions at national level [20–27]. Some provide as overview of the coal sector with a recommendation to develop a long-term framework for coal sector transitions, while others have analyzed the impact of decarbonization measures of ongoing policies (till 2016) in the coal sector. These studies have estimated an emission reduction of 20%–62% in alternative decarbonization scenarios compared to their business as usual scenarios. This study provides a quantitative assessment coupling a bottom-up technology-rich energy system model (AIM/Enduse India) with a macroeconomic computable general equilibrium (CGE) model to capture the wider, systemic implications of shifting away from coal, not only for the energy sector (and associated emissions) but also the socio-economic impacts. The main innovation of the study is that it analyzes the implications of the Indian commitments at COP26 and is one of the first studies exploring the long-term effects of the net zero goal. Furthermore, the study provides insights on challenges to achieve decarbonization of the Indian economy without compromising on energy security and energy affordability, but also on the opportunities from energy sector restructuring, including low-carbon technology diffusion, job creation in renewable energy and agriculture (to produce the required biofuels), and energy import reduction.

This paper looks into the most recent climate policy and net-zero declaration by India to address the socio-technical, socio-economic and financial implications of Indian shifting away from coal. Section 2 describes the model set-up and the scenario design used in this study. Section 3 explains in detail the model results, while Section 4 develops the key dialogues held at international and national level on a) the future of coal in India, b) impact on international coal trade, c) co-benefits and tradeoffs of coal transitions, and d) socio-economic implications of climate compatible development pathways in India. Section 5 concludes summarizing the significance and relevance of the study.

2. Methodology

2.1. Modelling Framework

This study provides a quantitative model-based assessment to address the socio-technical, macro-economic, and financial implications of India shifting away from coal. We have coupled the bottom-up technology-rich energy system model, AIM/Enduse India with a macroeconomic computable general equilibrium (CGE) model, GEM-E3, that provides details on the complex interactions of energy transition with the economy, capital and labour market.

2.1.1. AIM/enduse India

AIM/Enduse-India model **(**Fig. 1**)** has been used in the current study to capture the major sectors of the energy and environment systems in India and quantify the impacts of multiple objectives (climate change mitigation, energy and climate security) of existing and future policies related to emissions reductions, energy efficiency, addition of renewables etc. The model focuses both on energy supply (e.g. power generation, refineries, coal supply) and energy end-use sectors (industry, transport, buildings and agriculture) [10,24,28]. It is a national level model with high sectoral, temporal and technology granularity. The model has been developed to estimate the future development of primary and final energy mix, emissions from the energy system, electricity generation mix and capacity additions and related energy costs and prices for various sectors under alternative policy, socioeconomic and technology assumptions. In this study, we use the model to project the future coal demand and energy system transformation pathways of India in the context of NDC targets and net zero pledges. Further information about the model is provided in the supplementary information.

2.1.2. GEM-E3 model

GEM-E3 is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its complex interactions with the environment and the energy system. GEM-E3 allows for a consistent comparative analysis of policy scenarios since it ensures that the economic system remains in general equilibrium. In addition, it incorporates microeconomic mechanisms and institutional features within a consistent macro-economic framework. The model provides insights on the distributional aspects of long-term structural adjustments, in particular with regard to energy sector transformation and low-carbon transition. The GEM-E3 model is extensively used as a tool for policy analysis and impact assessment in the energy and climate fields [29–31].

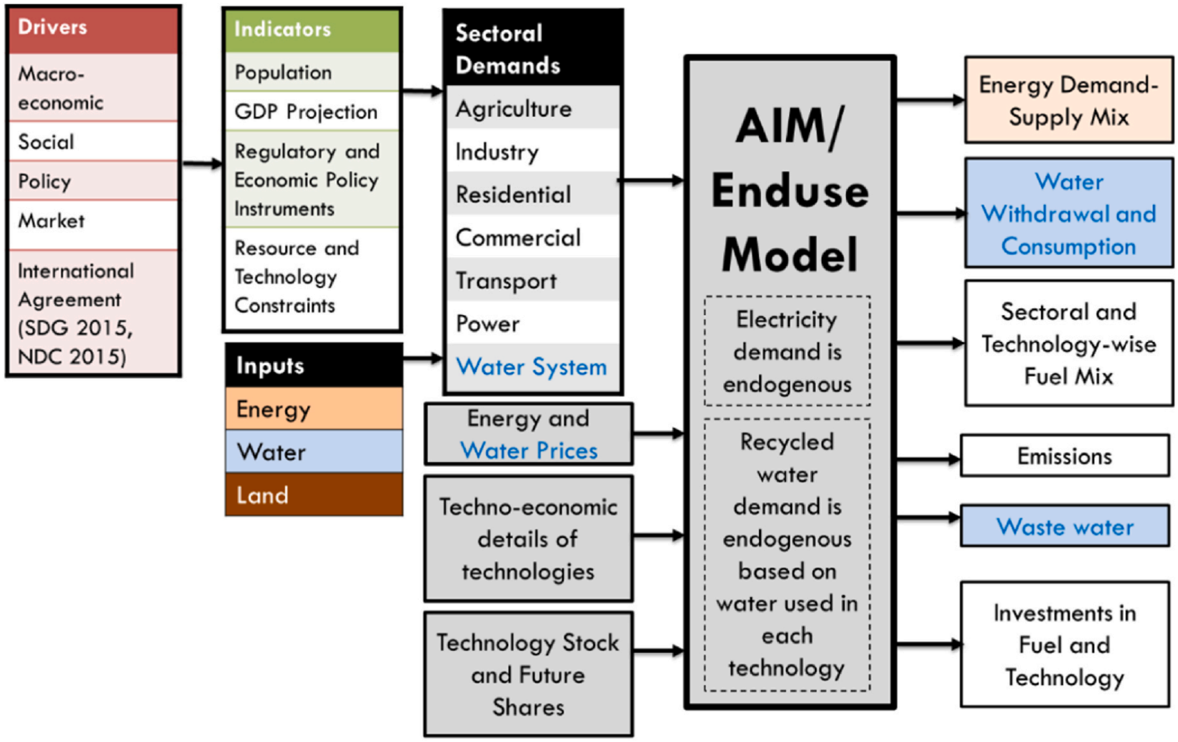

Fig. 1. Modified AIM/Enduse water-energy-land (W-E-L) modelling framework.

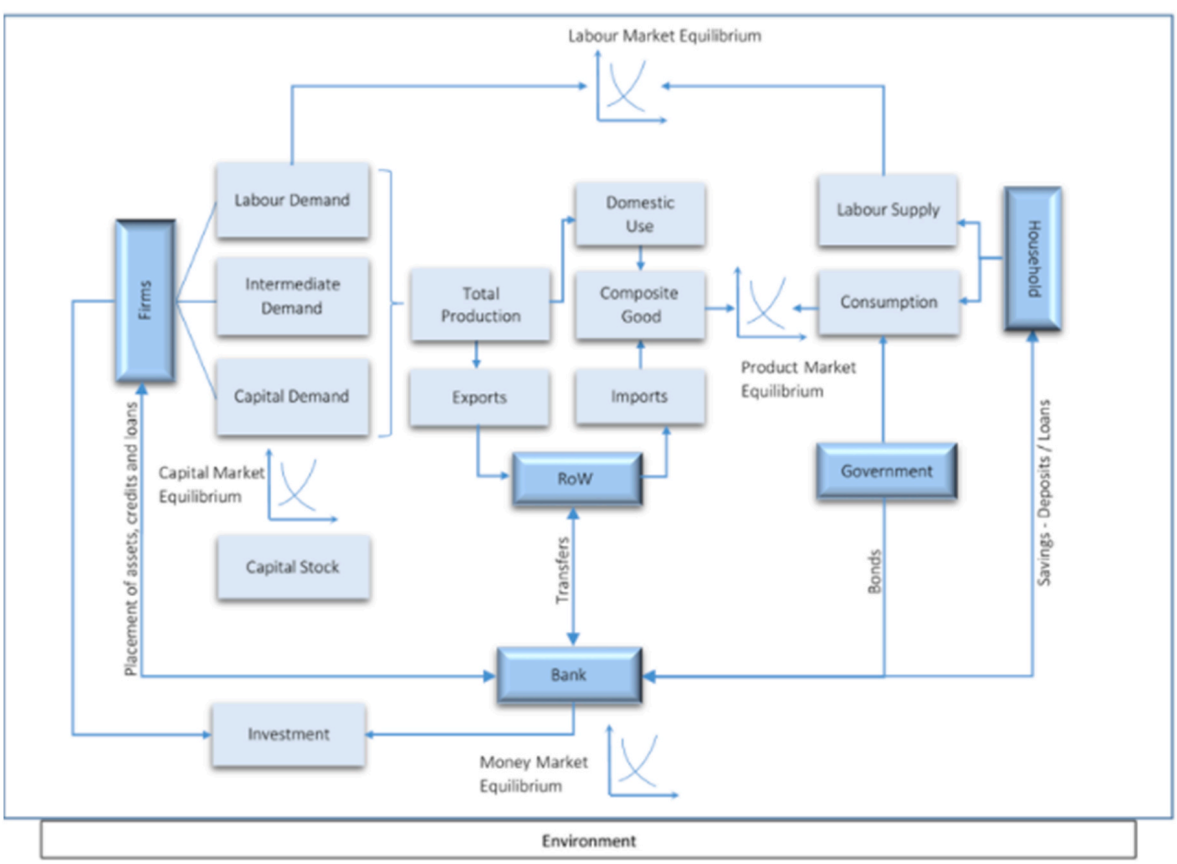

Fig. 2. Schematic representation of GEM-E3 Model.

GEM-E3 formulates separately the supply or demand behaviour of the economic agents which are considered to optimize individually their objectives (i.e. cost minimization for firms, utility maximization for households). The market derived prices guarantee global equilibrium in all markets, allowing the consistent evaluation of distributional effects of alternative policies [32]. It considers explicitly the market clearing mechanism and the related price formation in the energy, environment, capital, and product markets. Prices are computed by the model as a result of supply and demand interactions in the markets. GEM-E3 represents imperfect labor markets through involuntary unemployment, simulated by an empirical labor supply equation that links wages and unemployment levels through a negative correlation.

Different regions are linked through endogenous bilateral trade based on the Armington assumption. Production functions are based on a constant elasticity of substitution (CES) structure and include labor, capital, energy, and intermediate goods. The model formulates production technologies in an endogenous manner allowing for price-driven derivation of all intermediate consumption and the services from capital and labour. The model is dynamic, recursive over time, driven by accumulation of capital and equipment. Technology progress is explicitly represented in the production function, depending on research and development (R&D) expenditure by the private and public sector and considering spillover effects, based on the myopic expectations of the participant agents [33] (Fig. 2).

In recent years, the GEM-E3 model has been expanded with an enhanced representation of the energy sector and relevant emission reduction options to analyze climate mitigation policies [31]. In particular, a detailed power system model has been developed and soft-linked with GEM-E3 [34] to represent in a bottom-up manner the evolution of the electricity sector distinguishing thirteen power producing technologies (fossil-related -including CCS, nuclear, and several renewable energy technologies). In addition, GEM-E3 represents energy efficiency improvements and changes in fuel mix by sector, potential for electrification, bottom-up simulation of passenger and freight transport modes (with distinct technologies for passenger cars), link of biofuels with the agriculture sector and various emerging decarbonization options, including hydrogen, advanced biofuels and CCS. The analytical bottom-up representation of the energy sector allows GEM-E3 to quantify the socio-economic impacts of mitigation targets as it represents various climate policy instruments (including carbon pricing, clean energy subsidies, energy efficiency standards, coal phase out plans, and technology standards). The GEM-E3 model has been extensively used for energy and climate policy impact assessments, including the Energy Roadmap 2050 (European Commission 2011), Climate Package for 2030 (European Commission 2019) and the Clean Planet for All strategy (European Commission 2018).

2.1.3. Soft-linking of AIM-enduse India and GEM-E3 model

The methodological framework used in the study is similar to that of Fragkos et al., 2017 [35] and Vishwanathan et al., 2019 [29]; namely, it features a soft linkage between a bottom-up energy system (AIM/Enduse) model and the macroeconomic GEM-E3 model.

The AIM/Enduse India model includes a realistic representation of the energy system - both energy supply and demand- and captures elements that are not captured by the rigid CGE framework, including renewable energy potentials, electricity system operation constraints, cost-supply curves for technologies, and grid losses [29]. Therefore, in order to improve the simulation of the socio-economic impacts of climate pathways, the energy system results of AIM/Enduse (energy consumption by sector, electricity demand, power generation mix, penetration of electric and heating appliances) are used as an input into the GEM-E3 model that in turn can estimate the employment, sectoral production, trade, and macro-economic impacts for India. The soft-linking of AIM/Enduse India output to GEM-E3 is performed for.

- ❖ Power generation mix: GEM-E3 simulates the power production sector through a Leontief production function incorporating 13 power producing technologies. The coefficient shares are adjusted to reflect the power generation shares derived from the AIM/Enduse (for all the scenarios over 2020–2050 period).
- ❖ Energy mix in enduse sectors: In order for GEM-E3 to proxy the AIM/Enduse model results, modifications were made in fuel shares (between coal, oil, gas, electricity, solar and biomass) in industry, transport, and buildings incorporating the scenario projections of the AIM/Enduse India model. The soft-link process for the electrification and fuel mix of final energy demand in end-use sectors is described in Fragkos et al., 2018 [36].
- ❖ In addition to the energy system characteristics, the two models use harmonized assumptions for socio-economic development (population, GDP), carbon prices, and the costs of energy technologies

The integrated assessment is facilitated by the methodological and modelling enhancements in the GEM-E3 model allowing to consistently integrate energy system projections by technology and sector, ensuring the harmonization of energy system development in the two models. Data exchange between the two models is facilitated by the use of a spreadsheet-based template including a set of variables and parameters that are common to both models.

2.2. Scenario description

Three different transition pathways are analyzed to discuss alternative future scenarios for the Indian energy system and economy. Table 1 presents the policy measures and model inputs in each of the sectors across the scenarios. The same assumptions for energy and climate policy instruments by scenario are implemented in both models in order to ensure consistency and comparability of their scenario projections.

2.2.1. Baseline scenario

The scenario encompasses all the currently implemented policies included in the Indian National Action Plan on Climate Change (NAPCC), and National Determined Contribution (NDC) as submitted under the Paris Agreement in 2015. The scenario goals include: a reduction in GHG intensity of Indian GDP by 33–35% during 2005–2030 (NDC Goal 3) and increasing non-fossil energy share to 40% of total electricity capacity by 2030 (NDC Goal 4). Under the National Solar Mission (NSM), the renewable capacity targets are increased from 20 GW pre-Paris to 175 GW in the NDC document. The Baseline scenario also includes a reduction of transmission and distribution (T&D) losses to 15% through Restructured Accelerated Power Development and Reforms Programme (R-APDRP). Under the National Mission of Enhanced Energy Efficiency (NMEEE), specific targets have been introduced to about 480 industrial units for reducing their specific energy consumption under the Perform Achieve and Trade (PAT) scheme initiated pre-Paris (2013–2016), which continues to 2030 and beyond. Under the Faster Adoption and Manufacturing of Hybrid and EV (FAME), 30% of all new cars coming to the market will be electric by 2030. The transport sector assumes the ethanol blending of 5% as stated in the biofuel policy in India. The standards and labelling (S&L) programme covers air conditioners, ceiling fans, refrigerators, and TVs [2,3,10,24,37].

2.2.2. Enhanced NDC scenario (en. NDC)

The scenario encompasses all the on-going policies captured under the baseline scenario and the policies implemented after the NDC submission in 2015. In 2016, the government announced a major set of national sustainable development targets following the global Agreement on Sustainable Development Goals (SDG) in New York. These include but are not limited to electricity for all by 2019, 25 million LPG connections by 2019 (about 100 million achieved by February 2022), universal public health, universal primary education, and housing for all by 2022. This is in addition to selected sectoral, energy and climate

Table 1
Scenario Description used in this study.

Sector	Baseline Scenario	Enhanced NDC Scenario (En. NDC)	Climate Compatible Development Scenario (CCD)
Power production	175 GW renewables in 2030; Transmission and Distribution (T&D) losses reduce by 6–7%; Phase out old, inefficient fossil plants by 2040.	250 GW renewables in 2030; T&D losses decline by 8–10%; Phase out old, inefficient fossil plants by 2030.	500 GW renewables; T&D losses reduce by 8–10%; Phase out old, inefficient fossil plants by 2030.
Industry	Improve Energy Efficiency (EE) through Perform, Achieve, and Trade (PAT) Cycles.	Ratcheting EE through deepening of PAT Cycles in energy intensive sectors.	Ratcheting EE through widening and deepening of PAT Cycles in medium and small enterprises (MSMEs) in addition to large point sources (LPS).
Transport	Ethanol blending: 5%; EV penetration: 30% of all new cars by 2030.	Ethanol blending: 10%; EV penetration: 30% of all new cars by 2030.	Ethanol blending: 20%; EV penetration: 50% of all new cars by 2030.
Buildings	EE AC penetration: (i) reduce cooling demand across sectors by 10%–15% by 2040, (ii) reduce refrigerant demand by 10%–15% by 2040, (iii) Reduce cooling energy requirements by 5%–10% by 2040.	EE AC penetration: (i) reduce cooling demand across sectors by 10%–15% by 2040, (ii) reduce refrigerant demand by 10%–15% by 2040, (iii) Reduce cooling energy requirements by 5%–10% by 2040.	EE AC penetration: (i) reduce cooling demand across sectors by 20%–25% by 2040, (ii) reduce refrigerant demand by 25%–30% by 2040, (iii) Reduce cooling energy requirements by 25%–40% by 2040.

action policies, with relevant Sustainable Development Goals (SDG) to be achieved by 2030. In 2019, the 2030 target of non-fossil power capacity share was further ratcheted up to 450 GW (from 175 GW in Baseline). As the implementation had been gradual, for this study we assumed the solar target to be increased to 250 GW. Reduction in T&D losses improves to 8–10%, and old, inefficient power plants are phased down by 2030. In the industry sector, the government has rolled out six PAT cycles until 2025 with a total of 1073 designated consumers (DCs) widening to the 13 sectors, thus increasing the climate ambition in the industry sector relative to Baseline. In the transport sector, the share of ethanol blending increases to 10% by 2022. In the buildings sector, about 26 electric appliances are covered under mandatory and voluntary policy regimes. In this scenario, the GEM-E3 model, which has global coverage, assumes that all countries meet their NDC targets by 2030, as announced by December 2021. After 2030, the climate policy effort is extrapolated, by assuming that its stringency remains constant (but does not increase), in line with [38] with regional carbon prices increasing after 2030 with the same growth rate as GDP of each region.

2.2.3. Climate compatible development scenario (CCD)

The scenario ratchets the on-going policies and NDC targets to capture the pledge made by India at COP26 in order to shift towards net-zero emissions by 2070. This includes the targets below outlined in the Indian NDC as submitted in COP26. In particular: a) a further reduction of emission intensity of Indian GDP to 45% during 2005–2030; (b) an increase in the share of non-fossil-based energy resources to 50% of installed electric generation capacity; (c) to install 500 GW of renewable power generation capacity by 2030; (d) to mitigate 1 billion tonnes of carbon dioxide equivalent (btCO2e) by 2030 compared to NDC 2015 estimates [3]. In this scenario, after 2030 all countries (including India) are assumed to implement ambitious climate policies aiming to meet the Paris Agreement goals of well-below 2 °C (and make efforts to below 1.5 °C). Based on recent scientific literature [38], this means that the global carbon budget (i.e. cumulative carbon emissions) should be lower than 800 Gt by the end of the century [39]. This target is shown by the global GEM-E3 model to be met by imposing a universal carbon price across sectors that increases the cost to use fossil fuels. While acknowledging that the imposition of a globally harmonized carbon price will face challenges especially in developing countries, policy makers have not yet agreed on any specific framework to allocate the emission reduction effort (required to meet Paris climate goals) to individual countries.[2] So, the current study – in broad agreement with the literature and IPCC scenarios-assumes that the global mitigation effort is allocated in a cost-optimal manner to countries through the imposition of a global carbon price, assuming that governments would prepare the ground for comprehensive (pricing) measures that are socially acceptable, e.g. through the use of revenues [40]. In AIM-Enduse, India increases its climate policy ambition after 2030 with accelerated uptake of renewable energy in energy supply and demand, energy efficiency improvements, increased electrification of end-uses (e.g. through high uptake of electric vehicles in transport), larger biofuel blending and sectoral measures described in Table 1.

[2] India has coal cess (tax) for coal sector in addition to a market for trading energy saving certificated with about 13 industries. The Indian cabinet last year introduced the mandate to develop carbon markets. The market would cover emissions of carbon dioxide and also five other greenhouse gases valued in terms of their carbon dioxide equivalence. The compliance market will be obligatory for entities such as oil refining, steel, aluminum and cement, while voluntary market would be open to other entities. This new development is out of scope for the current study.

3. Results

3.1. Development of CO_2 emissions in India by 2050

All scenarios are projected to overachieve the NDC target of reduction in emission intensity of the GDP, which is estimated to be higher than 33–35% (NDC Goal 3) ranging between 45 and 55% in 2030 relative to the 2005 level. The cumulative carbon emissions between 2020 and 2050 range between 99 and 112 bt-CO_2 across these scenarios (Fig. 3). Coal based cumulative emissions amount to 50%, 44% and 38% of total CO_2 emissions in the Baseline, En. NDC and CCD scenarios respectively. When compared to the Baseline scenario, total CO_2 emissions in the En. NDC and CCD scenarios are reduced by 7–8% in 2030 and by 17–37% in 2050. Fig. 3 presents the aggregate[3] carbon dioxide emissions (coal, oil and gas) across sectors under various scenarios in India. The figure also shows coal-based carbon dioxide emissions (dotted line) for comparison. The trajectory for aggregate emissions is similar for enhanced NDC and CCD scenarios as the coal-based emissions may be replaced by oil and gas in some of the sectors.

3.2. CO_2 emissions in power generation and industrial sectors

Fig. 4 presents the carbon dioxide emissions from the power and industry sector, which consume almost all coal in India. The share of power sector emissions in total Indian emissions is projected to decrease from 42% in 2020 to 36% in 2030 and further to around 31% in 2050 in baseline. Similarly, the share of electricity-related emissions decreases to 31–32% in 2030 and 8–28% in 2050 in scenarios with more ambitious climate policies (En. NDC and CCD). This projected decline in the share of electricity-related emissions implies that power generation is relatively easier to decarbonize when compared with other major emitting sectors (industries, transport), as many low- and zero-carbon technological options (e.g. solar PV, wind onshore, small hydro, waste to energy) are already cost-competitive with conventional fossil fuel thermal power plants. In contrast, emission reductions are more difficult to achieve in energy end use sectors (industry sector in this case) due to the lack of cheap low-emission alternatives and the lack of appropriate policy measures to accelerate the uptake of low-carbon options in these sectors. The effect of energy efficiency improvement in the electricity based end-use devices is observed indirectly in the power sector through reduction in electricity demand.

The share of electricity-related emissions from coal (in electricity and industrial emissions) is projected to decrease from 60% in 2020 to 50%–55% in 2030 to 0–48% in 2050 under alternative scenarios, with coal disappearing from the Indian power mix by 2050 in the CCD scenario. This trend is observed due to a combined impact of: 1) increase in the deployment of renewable energy sources, 2) a decrease in transmission and distribution losses, 3) increase in fuel and technical efficiency in thermal based power plants and 4) deep decarbonization shift of base load away from coal and towards nuclear and large hydro, with storage providing flexibility to the power grid to balance the intermittency of variable renewables (wind and solar).

On the other hand, the share of industrial-related emissions[4] from coal is projected to increase from 40% in 2020 to 45%–50% in 2030 to 52%–100% in 2050 under alternative scenarios. This is mainly due to the drastic decrease in the share of emissions from the electricity sector, combined with limited options to reduce emissions from energy-intensive industries that require high-temperature heat, which in the medium term will be provided by fossil fuels with limited potential for electrification. As a result, the differences in industry-related emissions in India across alternative scenarios are negligible until 2030 and relatively limited even by 2050. Industrial emissions in India in the CCD scenario are about 20% lower than in the baseline scenario, due to the implementation of energy efficient programmes (PAT) in industries under National Mission Enhanced Energy Efficiency (NMEEE), the shift to natural gas (and away from coal) as an alternative source of energy, and the installation of Carbon Capture Utilization and Storage (CCUS)[5] facilities especially in energy intensive industries like steel and cement.

3.3. Development of coal use by sector

Figs. 5 and 6 illustrate the AIM-Enduse India model projections for coal demand by type and sector respectively in India over 2020–2050.[6] In the baseline scenario, the total coal demand is projected to increase from around 0.9 bt in 2030 to 1.1 bt in 2050 with an average annual growth rate of 0.82% over 2030–2050. The coking coal demand increases from 95 Mt in 2030 to 125 Mt in 2050. In 2020, about 70% of coal in India was used for electricity generation, whereas the share of industry is about 30%. In the baseline scenario, the share of the power sector decreases to about 52% in 2050, while the share of industry increases to about 48% in 2050. This is because the on-going, currently implemented policies in the electricity sector (e.g. the renewable capacity expansion targets) and the large cost reductions of renewable energy technologies lead to a rapid increase in the share of renewables, especially solar PV and wind onshore, while coal use for power production continues until 2050, but coal plays a smaller role in electricity than today. Therefore, coal demand in India is projected to increase modestly over 2030–2050, as a result of energy efficiency in power plants and a shift to renewables and electrification in all end-use sectors (industry, transport, residential and commercial sectors).

In the En. NDC scenario, the total coal demand is projected to decrease to around 0.58 bt in 2050 as a result of policies favoring the introduction of low-emission technologies instead of carbon-intensive use of coal in electricity and industrial sectors. The coking coal demand decreases by 2–15 Mt between 2030 and 2050. The share of coal used in the industry sector increases to about 68% (from around 30% today), while the share of the power sector decreases to about 32% in 2050, from 70% in 2020. In the CCD scenario, climate policies become even more ambitious, especially after 2030 and total coal demand is projected to decrease to around 0.31 bt in 2050. In this scenario, the electricity generation sector is projected to be fully transformed towards a low-emission paradigm with very high uptake of renewable energy technologies and phase out of old, inefficient, coal-fired power plants by 2050. This will also lead to stranding of recently built based assets. In this context, all coal in India is used by the industry sector. This is a result of the projected rapid increase in the share of renewables (especially wind and solar), accompanied with nuclear, large hydro, biomass,

[3] The aggregate emissions differ from coal based emissions as they also include emissions from oil (petrol, diesel and other sources) and natural gas based emissions from all sectors (power, industry, transport, building and agriculture).

[4] Industry emissions include the emissions from fuel combustion for energy as well as from industrial processes. Iron and steel sector consumes coal both for fuel combustion as well as a reducing agent (coking coal). Other industries mainly use coal for fuel combustion. We have included energy efficiency policies in addition to fuel shift policies in this sector."

[5] Academic literature about India's CCS readiness is diversified (Vishal et al., 2022). The CCUS Roadmap for India (TIFAC 2018) has recommended CO2-EOR and ECBM recovery as the primary drivers to implement CCS at a large scale in India. CCUS currently confined to industrial applications. India has pilot based demonstration project (industry sector), utilization facility (power sector) and enhanced oil recovery pilot study (oil sector) installed in the past decade. India has set up a couple of National centres, established a Mission Innovation Challenge on CCUS and measure to accelerate CCS technologies. India is in the process to develop policy framework to encourage implementation and scale up the technologies in both power and industry sector.

[6] Further information on total primary energy mix and generation mix can be found in the supplementary information.

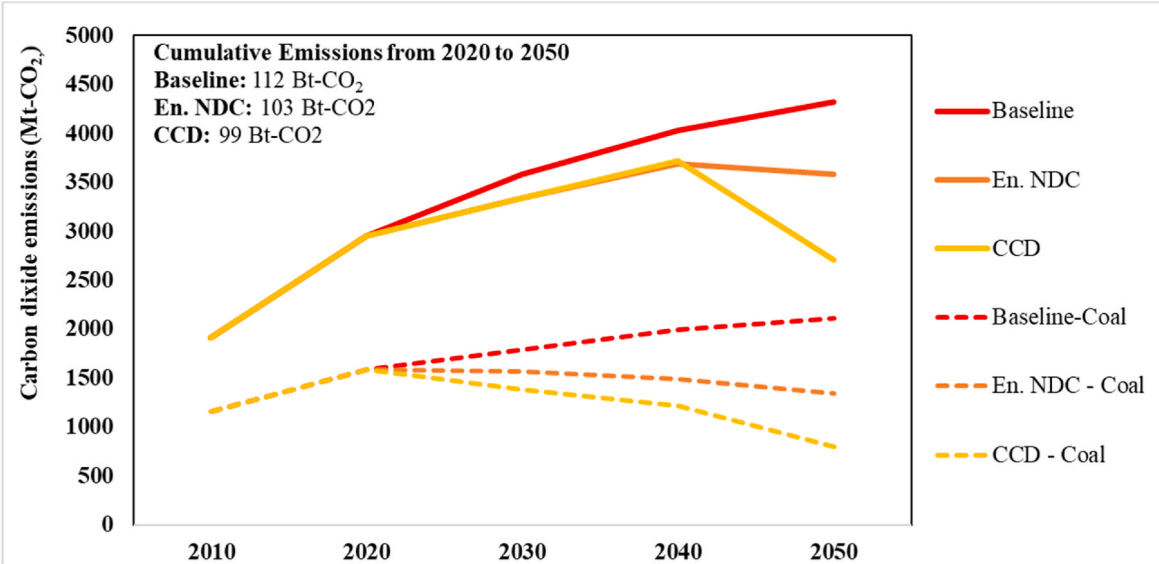

Fig. 3. Aggregate carbon dioxide emissions in India across all sectors and from coal under all the scenarios.

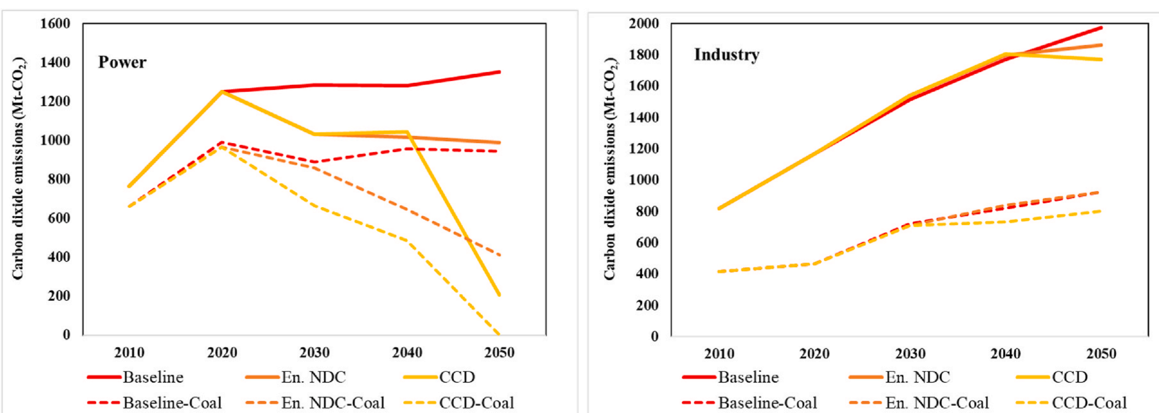

Fig. 4. Aggregate total and coal-based carbon dioxide emissions from power and industry under alternative scenarios.

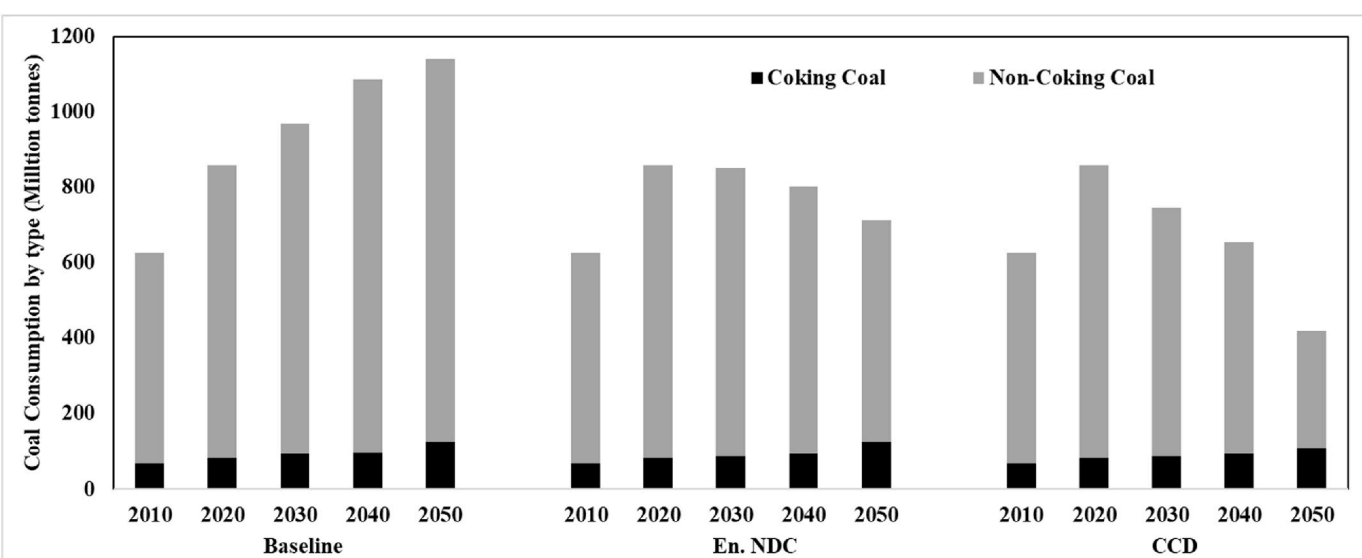

Fig. 5. Coking and non-coking coal consumption across all the scenarios in India.

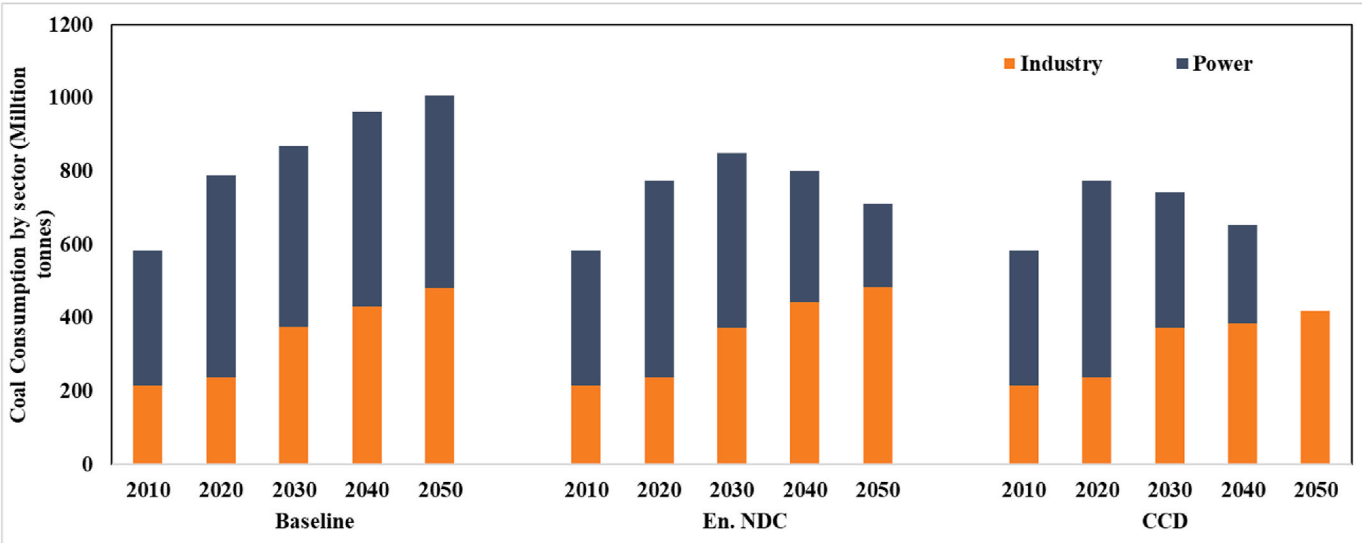

Fig. 6. Coal consumption by sector across all the scenarios in India.

and small share of gas after 2030 in the power sector. In the CCD scenario, both power and industry sectors become more energy and carbon efficient and heavily reduce their reliance on coal by 2050.

3.4. Socio-economic impacts of moving towards a low-carbon economy

Moving towards a low- or zero-carbon economy results in a large-scale transformation of the Indian economic systems, energy mix, labor markets, and production processes. Decarbonization involves increased upfront capital expenditures - as low-emission technologies are more capital intensive and commonly have higher risks than incumbent fossil fuel options- and lower energy purchasing costs in the long term [41]. GEM-E3 (as a CGE model) assumes full and optimal use of available capital resources in the baseline under financial closure. Therefore, the reallocation of investment towards low-emission technologies (especially in the CCD scenario) puts pressure on the capital markets and leads to "crowding-out" effects; firms and households finance their clean energy investment by spending less on other (non-energy) commodities and investment purposes. Overall, decarbonization is driven by the replacement of fossil fuel-intensive options

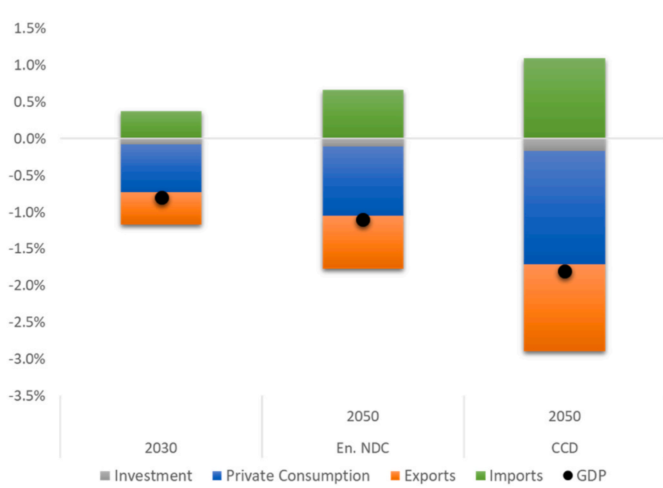

Fig. 7. Decomposition of Indian GDP changes in En. NDC and CCD Scenarios relative to Baseline for 2030 and 2050. The contribution of each component reflects its change from Baseline levels expressed as a share of GDP in 2030 and 2050.

and infrastructure for low- and zero-carbon technologies and climate ventures [41].

High carbon prices increase the cost of energy services for firms and households and hence production costs throughout the economy and have a depressing effect on consumption and GDP. We find that the En. NDC and CCD scenarios have only a limited impact on economic growth, with Indian GDP declining by 0.8% in 2030 and 1.1%–1.8% in 2050 relative to baseline (Fig. 7), even without quantifying the benefits related to avoided climate impacts, air quality and human health [42]. Our results are in the lower range of the IPCC AR5 estimates [43] which showed consumption losses of 2–6% in 2050 to limit temperature increase to less than 2 °C. This is due to the endogenization of technology learning for low-carbon technologies in the GEM-E3 model through learning by doing and learning by research mechanisms, which is described in detail in Refs. [44,45]. This means that the increased adoption of low-carbon technologies in ambitious climate policy scenarios would lead to a reduction in their costs through learning by doing and consolidated economies of scale, while also creating new industries for clean energy equipment [46]. These implications would tend to reduce the crowding out effects – as investment required for decarbonization are smaller- and mitigation costs relative to IPCC estimates and conventional CGE models 51]. Mitigation costs tend to increase with the climate ambition as the Indian economy currently has a high carbon intensity and high reliance on coal, which should be significantly reduced by 2050 to meet the CCD climate targets. However, the GDP growth remains particularly high in all scenarios with a limited decline from 5.2% p. a. Annually over 2020–2050 in baseline to 5.1% p. a. In CCD scenario. This result clearly illustrates compatibility of Indian NDC targets and net zero plans with robust economic growth.

Investment in low-carbon technologies and energy efficiency increase in the CCD scenario, which may pose challenges for mobilizing and directing available funds towards these options. This implies a potential "crowding-out" effect, leading to a small reduction of investment levels from baseline Scenario due to stresses in capital markets and the declining economic activity. In contrast, private consumption is the main contributor to GDP losses (Fig. 7), as production costs and prices increase due to carbon pricing and the reallocation of resources. The ambitious climate policies imposed in CCD influence the competitiveness of Indian firms in international markets, as exports decline from baseline due to increasing production costs, while imports also decline driven by lower domestic consumption. The high carbon intensity of Indian manufacturing firms relative to major international competitors implies that their competitiveness deteriorates with the imposition of climate policies[7]; thus Indian trade balance deteriorates by 0.2% points (p.p.) of GDP by 2050 (i.e. Indian exports decline more than imports in the CCD scenario relative to baseline). In terms of sectoral production, both En. NDC and CCD scenarios induce losses in carbon-intensive sectors (e.g. coal industry, oil refineries, manufacturing of metals, chemicals, cement, paper and pulp), which are not fully counter-balanced by the increasing production of the electricity sector (due to electrification), agriculture (due to biofuels), electric vehicles and other low-carbon technologies.

Climate policy impacts on employment are driven by two contradictory trends: on the one hand, declining GDP tends to reduce labour demand; on the other, low-emission technologies have higher labor intensity on average compared to fossil fuels [47–49] and thus the economy has a more labor-intensive structure. As described in Ref. [50], the projected job effects depend on the modelling approach (neo-Keynesian vs neo-classical), the climate policy ambition, the carbon revenues recycling scheme, the flexibility of labor markets, the trade position of a country (especially related to fossil fuels and clean technologies) and the availability of labor with the right skills for the emerging sectors. Under the specific GEM-E3 assumptions, CCD scenario impacts on total employment in India are limited and lower than GDP impacts, with total jobs declining by 0.5% in 2030 and 1% in 2050 relative to baseline (the impacts of En. NDC scenario are even lower with 0.6% employment reduction in 2050 from Baseline levels). This result is in line with scientific literature on projected employment impacts of decarbonization across major economies, e.g. using a suite of models show employment reduction around 0.5%–2% due to decarbonization in Japan [51], while project that employment would be around 0.3%–3% lower across G-20 economies in a strong decarbonization scenario compared to BAU [52], and show that the implementation of the revised NDCs would reduce employment by 0.1%–0.8% across major economies in 2030 [53].

Decarbonization leads to large structural shifts in employment across sectors, driven by a large reduction in jobs in the fossil fuel industry due to the phase-out of coal and declining demand for oil and natural gas, leading to changes both in job locations, labour skill-sets and education requirements. Our analysis shows that about 60% of the fossil jobs under baseline in 2050 will be eliminated in the CCD scenario (Fig. 8). As most jobs related to fossil fuels, especially coal-jobs, are concentrated in the east of the country, this result points to the need for complementary policies to ensure a just transition for Indian workers, especially focusing on regions and communities that massively depend on coal activities.[8] On the other hand, increased electrification of energy end uses combined with the uptake of more labor intensive renewable energy technologies (e.g. solar PV) draws workers from other sectors into the electricity sector, with most solar-related jobs created in west India and wind jobs in Gujarat and south India. In the CCD scenario, green jobs will increase by about 5 million relative to the Baseline scenario in 2050 (Fig. 8), with around 4 million created in the renewable energy sectors (mainly solar PV and wind power), around 300 thousand in the production of biofuels and around 500 thousand in the manufacturing of clean energy technologies (electric cars, batteries, renewable energy).

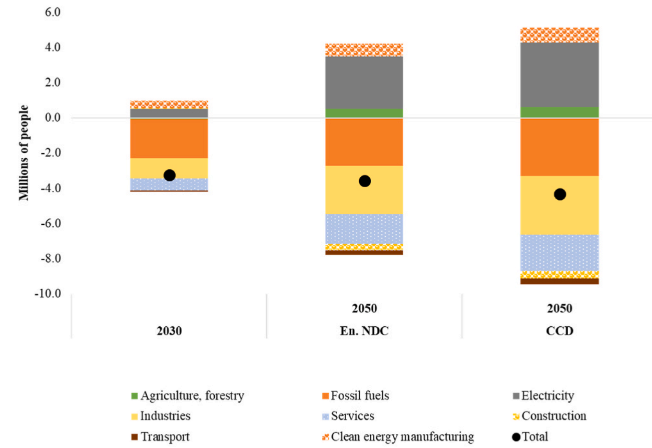

Fig. 8. Changes in the number of jobs in India in 2030 and 2050 (En. NDC and CCD scenarios relative to baseline scenario).

Our analysis shows that the increased jobs in the electricity sector counterbalance the jobs lost in fossil fuel industries, but the reallocation of workforce from the coal mining to renewable electricity should be accompanied with measures to ensure that workers from declining sectors develop the required skills with customized retraining programmes (Fig. 8). Job shifts also occur outside the energy sector, with some sectors negatively affected by increasing production costs and lower demand (e.g. energy-intensive industries, services), while others benefit from the transition to a low-carbon economy (e.g. agriculture due to increased demand for biofuels, sectors manufacturing clean energy technologies). Overall, the sectoral shifts induced by the transition are not very large in magnitude (as they directly influence only about 2% of Indian labor by 2050). Our analysis indicates that strong decarbonization policies need to be accompanied by complementary policies to ensure that the transition will not cause social disruptions, especially in regions and sectors heavily dependent on coal activities. In this context, reskilling programmes may facilitate the transition and reduce potential mismatches between demand and supply for specific labor skills for green sectors, while complementary measures (e.g. using a part of the carbon revenues to reduce labour taxes) are needed to boost domestic employment and support the labour market, especially in most vulnerable regions.

4. Discussion and policy implications

It is evident that the future of the coal industry in India hinges on power and industry transformation in the coming decades and on the ambition of climate policy measures implemented to ensure that India meets its net zero emission pledge by 2070.

4.1. Future of coal

The decrease of coal use in the En. NDC and CCD scenarios in the electricity sector is due to the combined impact of: 1) increased uptake of renewable energy (mostly solar PV and wind), 2) a decrease in transmission and distribution losses, 3) an increase in fuel and technical efficiency in thermal based power plants and 4) a shift of base load to

[7] The model-based results will be affected by the introduction of border carbon taxes, like the EU CBAM. The introduction of an EU CBAM tax on Indian trade balance will negatively affect the level of the Indian exports to EU for each CBAM sector, but it will benefit the level of Indian exports to non-EU countries as non-EU countries will substitute imports from EU with imports by other countries including India. The net effect on Indian balance of trade would be very small, especially in the CCD scenario context where all countries adopt high carbon pricing and this is why the study does not assess such a scenario.

[8] The just transitions policy framework will be complex and needs social dialogue at a larger scale when compared to the case of South Africa, and Indonesia. There is need of institutions at local, state, regional, national level along with international support to develop policies across all ministries to transform the current coal-intensive economy. It requires regional and local planning of the coal dependent region and districts, and diversification of these economies for the coming decades The central, state and local governments need to work in partnership with private, non-governmental organization and citizens in addition to the stakeholders in the entire coal supply chain to implement the transitions. The process requires social inclusion to especially empower the marginalized stakeholders from low socio-economic background. Finally, the process will require finance and investment to transform and support the structure of the local, state and national economy.

nuclear and large hydro, with storage providing flexibility to the power grid to support the rapid uptake of variable renewable sources. Industrial emissions also decline relative to the baseline scenario due to increased electrification combined with a decarbonized power grid in addition to the implementation of the energy efficient programme (PAT) under the NMEEE and installation of CCUS, especially in energy intensive industries like steel and cement.

India's current NDC and on-going development and economic policies have already played a crucial role in reducing carbon emissions intensity of GDP. Coal sector policies that are relevant include a) improvement of coal quality to increase energy efficiency of existing production capacity, b) revising coal cess (tax) from INR 50/t (37 cents/t) in 2010 to Rs 400/t (2.95 US$/t) in 2016–17. In the electricity sector, there are several policies to induce a shift towards low-carbon electricity generation including: a) phasing out of old, inefficient power plants and replacement with new supercritical plants with higher efficiency, b) adjusting the power market design to more efficiently integrate renewables and thermal power generation, and c) removing existing barriers to the achieving India's current renewable energy goals in the power sector.

The feasibility of the deep decarbonization scenario towards meeting the new net zero pledge by 2070 is dependent on various factors ranging from investments to low- and zero-carbon options, relevant technology transfers, capacity building to social acceptance of new, clean technologies. The industry sector will also become more energy efficient, however the model-based analysis illustrates the challenges and large difficulties to abate emissions due to coal combustion and industrial processes without significant investments in alternative, low-emission technologies (e.g. CCS and CCU), which until now are very costly and at low Technology Readiness Levels (TRL).

For example, in the industry sector, the emissions from coal can be reduced by the installation of appropriate CCUS technologies at selected locations in India. CCUS could be an essential component of Indian energy policy going forward, especially in the period after 2030, with a potential to reduce emissions by around 780 Mt each year at under US $60/t-$CO_2$ and around 1000 Mt at US$75/t-$CO_2$ [49,54]. Social acceptability, geological uncertainties, and environmental risks due to leakage of carbon dioxide remain a severe matter raising social and political acceptability concerns and reducing the prospects of large CCUS uptake globally and in India. For the past decade, the current gas capacity in India has been underutilized. However, public sector undertakings (PSUs) and the private sector recently switched from coal to gas due to the lack of coal supply, increasing electricity demand, and cheaper prices (especially during COVID19). In the CCD scenario, the social acceptability of nuclear power may pose an additional challenge for the Indian energy sector transformation depending on its fuel availability and geographical location.

4.2. Coal imports and international trade

Imports help to secure supplies when a country faces coal shortages. India has been a major importer of coal in the last decade as a result of rapidly increasing domestic demand for coal to fuel the growing economy. India imported most of its coal from Indonesia, Australia and South Africa in the past few years. So on the international coal trade front, if the central government retains the suggested zero-import policy for steam coal, India will still need to domestically produce at least a minimum of 75–100 Mt of steam coal to meet the demand from its power plants (designed for imported coal). Coal washing has already been discontinued in India. Fig. 9 presents the estimated imports and domestic coal production required in the next three decades in each of the policy scenarios. In the baseline scenario, coal imports are assumed to continue but decrease from 248 Mt in 2020 to about 200 Mt in 2050, as domestic production of good quality coal will increase in the next three decades. However, the large reduction of coal demand in the CCD scenario after 2030, implies that coal imports are even lower in this scenario, estimated to be in the range of 75–100 Mt in 2050.

4.3. Co-benefits: Emissions, land pollution, and air pollution

Emissions and pollution from coal mining operations are significantly less when compared to the use of fossil fuels by power plants and other enduse sectors (e.g. coal use in industries). Emissions from coal mining are projected to be around 30.5 MtCO_2 in the baseline scenario (accounting for 1.44% of total Indian CO_2 emissions), around 18.3 MtCO_2 (1.36. % of total Indian CO_2 emissions) and 9.6 MtCO_2 (1.19. % of total Indian CO_2 emissions) in the En. NDC and CCD respectively in 2050.

Environmental issues relating to land degradation, deforestation, air and water pollution result from coal mining activities [55]. Drastic decrease in coal demand results in the amount of overburden (soil layer that needs to be removed in order to access the ore being mined) reduced by 780 million cubic meters (Mcum) and 1338 Mcum in En. NDC and CCD scenarios respectively when compared with the baseline scenario in 2050.

Indian coal is of high ash content (up to 45%). More than 80% of ash generated is being utilized especially by the cement and fertilizer industry. The government is working on avenues to increase the utilization of ash to 100%. Similar to the decrease in overburden, the amount of ash generated was reduced by about 146 Mt (40%) and 251 Mt (69%) in En. NDC and CCD scenarios respectively when compared with baseline in 2050. With increasing coal mining activities, land acquisition, reclamation and rehabilitation (R&R) have also increased in the past few years. Coal India Ltd. Has created 2.4 ha of plantation for every hectare of land used for coal mining. This is in response to offset its Scope 1 emissions and to assist in achieving NDC goal 5 (creation of additional carbon sink).

Power sector contributes to 80% of mercury emissions, 60% of particulate matter (PM_{10} and $PM_{2.5}$) emissions, 45% of sulphur dioxide (SOx), and 30% of oxides of nitrogen (NOx) in India. With new pollution norms, installation of retrofits will help remove the emissions considerably. In the context of ambitious climate policies and reduced coal consumption in the CCD scenario, air pollutants are projected to decline by 100% in 2050 from 2020 levels.

4.4. Tradeoffs: Stranded assets (coal mines, power plants, jobs)

India's current economy is heavily dependent on coal. Stranded assets in the form of unutilized coal reserves and coal based power plants in addition to jobs will increase as a consequence of ambitious climate policies especially in the CCD scenario will be one of the major tradeoffs in both coal and power sector. About 225–230 billion tonnes of coal will remain unutilized until 2050 and the total cost of it would be roughly around 6.5–6.8 trillion USD (cumulative). As a result of multiple physical constraints and dynamics of national and international markets, coal-fired power plants have been stranded in the past few decades.[9] In this study, we present that coal based assets (mines, power plants, supply chain, labor) will be impacted to due to ambitious climate based policies.

5. Conclusions

India is one of the important countries that is and will continue to play a crucial role in climate action along with the European Union, the

[9] In the past couple of decades, coal power plants have been stranded temporarily and a few times permanently due to lack of timely coal supply, water scarcity in the region, air pollution issues (as expanding cities have engulfed the power plants), financial instability (not receiving the payment from end use consumers) and most recently due to competing renewable technology prices.

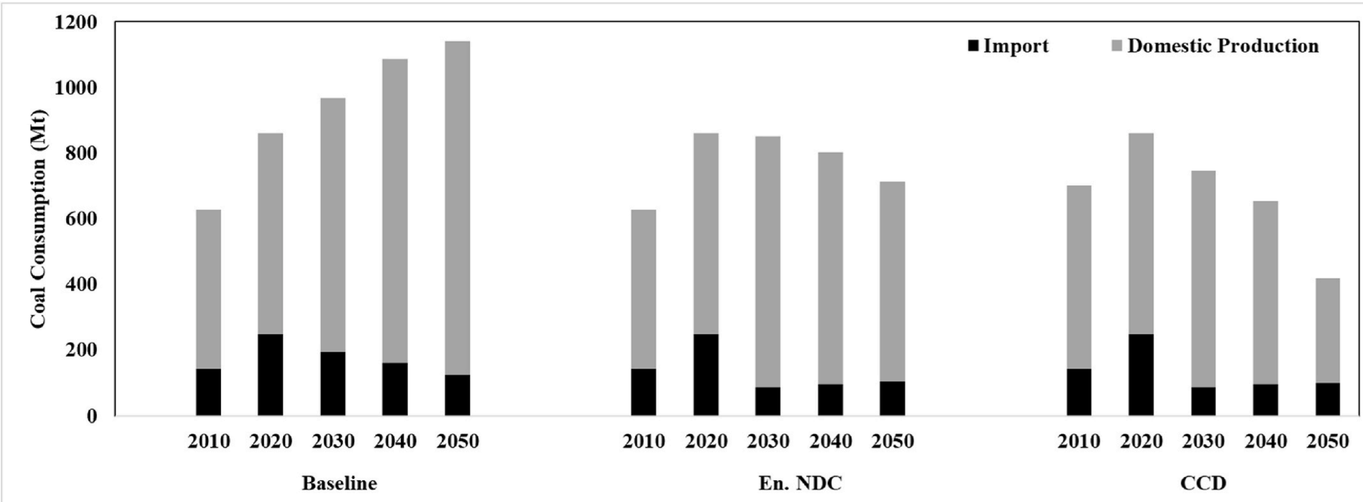

Fig. 9. Imports and domestic production of coal across all the scenarios in India.

United States of America and China. At the same time, China, India, USA, Germany, Russia, Japan, South Africa, South Korea, Poland, Australia, Turkey and Indonesia, together account for over 88% of global coal extraction and consumption per year. Individual coal dependent developing countries like India have given priority to energy security and economic-social-political development resulting in a continued reliance on coal, which may continue for the coming decades if socio-economic and environmental priorities do not radically change. There is a need for an international mechanism to provide the required finance and low- and zero-carbon technology to support the phase out of coal use in such countries that are still in early development phases and want to combine economic growth with ambitious climate action.

This study attempts to provide a state-of-the-art assessment of the future of coal transitions under alternative Indian energy system transformation pathways up to 2050. The technology, emission and socio-economic implications of the transitions are assessed by selecting three alternative scenarios including different levels of climate policy ambition. The model-based analysis shows that there is still an enormous scope of energy sector transition in India in order to decarbonize its economy and move towards the net zero goal by 2070. India will require to not only restructure its coal-based electricity and industry sector as well as its transport and buildings sectors, but also will need to implement the process in an equitable manner, ensuring that no state, region, or household is left behind.

The energy sector transformation resulting from the accelerated uptake of non-fossil energy (mostly solar and wind), the enhanced electrification of energy and mobility services, and energy efficiency improvements will also bring substantial co-benefits for Indian development. These include reduced local air pollution and thus improved human health (especially in large cities), reduction in water and land pollution as well as reduced energy imports thus improving India's trade balance and energy supply security. However, to government requires to plan regulatory and economic instrument to encourage the uptake of CCS and CCU technologies in industry sector in the coming decade to enhance decarbonization.

The socio-economic analysis ascertains that transition towards a low-carbon economy will massively impact the production processes, trade balance, labor markets, sectoral production, and consumer preferences in India. Decarbonization is a complex process requiring system-wide changes impacting all sectors, firms and households in India, creating both challenges and opportunities. The massive uptake of low- and zero-carbon technologies will reshape the India economy and labor markets, inducing large shifts from fossil fuels and carbon-intensive activities towards renewable energy sources. In this context, regions, communities and businesses that depend on coal industries will face reduced demand and income and thus they need to restructure their economies and develop labor skills required for the green sectors. In this context, the government can support coal transition by developing reskilling programmes and capacity development measures to support the creation of new labor skills in workers moving from the declining coal industry to the emerging clean energy sectors (e.g. solar PV, wind, advanced biofuels). In addition, policies should support labor retirements in the coal industry, as well as provide the required education and job security for the children of coal workers.

This sectoral restructuring will also create opportunities for those regions that have high renewable energy potentials, as most jobs related to PV, wind power, and biofuels will be domestically created, or for clean energy businesses and their supply chains (e.g. metals used in wind plants, agriculture used to develop biofuels). To ensure a fair transition, farmers and landowners should be actively involved in solar and wind park development, for example through duly providing them fair compensation to lease their lands, retaining them as part of renewable energy options as land owners (and not land sellers), or providing them with clean and secure energy as well as with the appropriate education and infrastructure.

The energy transition will also impact trade flows, as the competitiveness of Indian industries will be impacted by changing energy and electricity prices. This calls for the establishment of some protective measures for the Indian energy-intensive and trade-exposed industries (e.g. cement, steel, chemicals, paper and pulp), discussed in the EU in the form of Carbon Border Adjustment Mechanism. In addition, the large financial and low-carbon technology requirements should be met by a combination of domestic and international efforts to support the reduction of coal use in countries like India, which are still in early development phases and strive to combine economic growth with climate action.

Our analysis shows that the increased activity in clean energy sectors and their supply chains counterbalances the activity losses projected for fossil fuel sectors (especially coal mining) and carbon-intensive manufacturing sectors. Therefore, the low-carbon transition would have only marginal impacts on aggregate GDP by 2050, showing that the transition to a net zero emissions economy is compatible with robust economic growth. However, the potential negative impacts of the transition to specific regions, sectors, and households, should be alleviated and effectively managed with appropriate policy measures, in order to ensure a just transition with minimal social hardship for low-income households and enhanced social equity.

One of the major limitations of the study is feasibility assessment of these ambitious climate policy scenarios in terms of energy supply due to uncertainties. These will depend on multiple factors which include (a) the selected energy source (natural gas imports, domestic or imported coal, nuclear fuel production/import and supply chain) replacing the base load, (b) future development of renewables, (c) development and production of electric vehicles and battery storage and (d) social acceptability and geological uncertainties of CCUS technologies. These are areas that require further sub-regional/sub-national level analysis.

Credit author statements

Saritha Sudharmma Vishwanathan: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Review and Editing, Visualization; Panagiotis Fragkos: Conceptualization, Methodology(GEME3), Data curation (GEME3), Formal analysis (GEME3), Writing – original draft, Review and Editing, Visualization, Funding acquisition; Konstantinos Fragkiadakis: Methodology(GEME3), Data curation (GEME3), Formal analysis (GEME3), Amit Garg: Writing – review & editing, Funding acquisition.

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.

Data availability

Data will be made available on request.

Acknowledgements

This material has been produced under the Climate Compatible Growth programme, which is funded by UK aid from the UK government. However, the views expressed herein do not necessarily reflect the UK government's official policies.

The research leading to this study has received partial funding from the DDP Initiative (ddpinitiative.org), the International Climate Initiative (IKI), the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) under grant agreement No 18_I_326 (DDP BIICS); European Union Horizon 2020 research and innovation program under grant agreement No 101003866 (NDC ASPECTS) and the Indian Institute of Management Ahmedabad. The views expressed in this study do not reflect the Indian government's official policies. We would like to acknowledge the National Institute for Environmental Studies for supporting the AIM/End-use model. Finally, we sincerely thank the editors and anonymous reviewers for their critical feedback which has helped us significantly improve the paper.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.esr.2023.101152.

References

[1] Ministry of Environment, Forest and Climate Change, Government of India. India's National Action Plan on climate change, 2008.
[2] Ministry of Environment, Forest and Climate Change, Government of India, 2015. India's Intended Nationally Determined Contribution.
[3] Press Information Bureau, Government of India, National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow, 2021.
[4] Ministry of Environment, Forest and Climate Change, Government of India, India, 2021. : Third Biennial Update Report to the United Nations Framework Convention on Climate Change.
[5] Global Energy Monitor, Boom and Bust 2021 - Tracking the Global Coal Plant Pipeline, 2021. https://globalenergymonitor.org/wp-content/uploads/2021/04/BoomAndBust_2021_final.pdf. (Accessed 15 December 2021).
[6] S.C. Singh, CEA Projections Show No New Coal Energy Projects in 10 Years, The Economic Times, 2022. https://economictimes.indiatimes.com/industry/renewables/cea-projections-show-no-new-coal-energy-project-in-10-years/articleshow/89418040.cms. (Accessed 8 February 2022).
[7] Climate Action Tracker, India. https://climateactiontracker.org/countries/india/, 2021. (Accessed 15 July 2021).
[8] Central Electricity Authority, National Electricity Plan,, ume I, Ministry of Power, Government of India, 2018.
[9] S. Narain, India's new climate targets: bold, ambitious and a challenge for the world, Down Earth (2021). https://www.downtoearth.org.in/blog/climate-change/india-s-new-climate-targets-bold-ambitious-and-a-challenge-for-the-world-80022.
[10] S.S. Vishwanathan, A. Garg, Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India, Climatic Change 162 (2020) 1877–1891.
[11] F. Harvey, A. Morton, J. Watts, COP26 Emission Pledges May Limit Global Heating to below 2C, The Guardian, 2021. https://www.theguardian.com/environment/2021/nov/03/cop26-emission-pledges-could-limit-global-heating-to-below-2c-india. (Accessed 11 February 2022).
[12] DW, India only G20 nation doing its 'fair share' to meet 2-degree goal — report (2021). https://www.dw.com/en/india-only-g20-nation-doing-its-fair-share-to-meet-2-degree-goal-report/a-55657420. (Accessed 11 February 2022).
[13] U. Goswami, India Set to Update 2030 Climate Targets under the Paris Agreement, The Economic Times, 2021. https://economictimes.indiatimes.com/news/india/india-set-to-update-its-2030-climate-targets-under-paris-agreement/articleshow/87098192.cms?from=mdr. (Accessed 15 December 2021).
[14] Central Electricity Authority Monthly Report, Installed Capacity, India, 2010.
[15] Central Electricity Authority Monthly Report, Installed Capacity, India, 2022.
[16] Central Electricity Authority Monthly Report, Generation Report, India, 2022.
[17] Draft National Energy Policy 2017, Ministry of Power, Government of India, 2017.
[18] Sustainable Development Goals (SDG), India Index and Dashboard 2020-21, March 2021.
[19] N. Höhne, M.J. Gidden, M. den Elzen, et al., Wave of net zero emission targets opens window to meeting the Paris Agreement, Nat. Clim. Change 11 (2021) 820–822, https://doi.org/10.1038/s41558-021-01142-2Van soest et al 2021.
[20] A. Malik, C. Bertram, J. Despres, J. Emmerling, S. Fujimori, A. Garg, E. Kriegler, G. Luderer, R. Mathur, M. Roelfsema, S. Shekhar, S.S. Vishwanathan, Z. Vrontisi, Reducing stranded assets through early action in the Indian power sector, Environ. Res. Lett. 15 (2020), https://doi.org/10.1088/1748-9326/ab8033. https://iopscience.iop.org/article/10.1088/1748-9326/ab8033.
[21] T. Spencer, R. Pachouri, G. Renjith, S. Vohra, Coal Transition in India, Technical Report, TERI Discussion Paper, New Delhi, 2018.
[22] T. Spencer, M. Colombier, O. Sartor, A. Garg, V. Tiwari, J. Burton, T. Caetano, F. Green, F. Teng, J. Wiseman, The 1.5°C target and coal sector transition: at the limits of societal feasibility, Clim. Pol. 18 (2018) 335–351.
[23] D. Gupta, F. Ghersi, S.S. Vishwanathan, A. Garg, Macroeconomic assessment of India's development and mitigation pathways, Clim. Pol. (2019) 1–21.
[24] S.S. Vishwanathan, A. Garg, P.R. Tiwari Shukla, India in 2°C and well below 2°C worlds: opportunities and challenges, Carbon Manag. 9 (2018) 459–479.
[25] L. Lawrenz, B. Xiong, L. Lorenz, A. Krumm, H. Hosenfeld, T. Burandt, K. Löffler, P.-Y. Oei, C. Von Hirschhausen, Exploring energy pathways for the low-carbon transformation in India—a model-based analysis, Energies 11 (2018), https://doi.org/10.3390/en11113001.
[26] S.S. Vishwanathan, A. Garg, V. Tiwari, Coal transitions in India. Assessing India's energy transition options, IDDRI and Climate Strategies (2018).
[27] Tiwari, et al., Assessing Possibilities for Coal Continuance in India under Climate Constraints, 2023. https://www.sciencedirect.com/science/article/pii/S1750583622002298.
[28] S.S. Vishwanathan, A. Garg, V. Tiwari, M. Kapshe, T. Nag, SDG Implications of Water-Energy Systems Transitions in India under NDC, 2 °C and Well below 2 °C, 2021, https://doi.org/10.1007/s10584-019-02616-1.
[29] Vishwanathan, et al., Energy System Transitions and Macroeconomic Assessment of the Indian Building Sector, 2018. https://www.tandfonline.com/doi/abs/10.1080/09613218.2018.1516059.
[30] Fragkos, P et al. Reducing the Decarbonization Cost Burden for EU Energy-Intensive Industries, https://www.mdpi.com/1996-1073/14/1/236.
[31] Paroussos L. et al. Macro-economic analysis of green growth policies: the role of finance and technical progress in Italian green growth, https://link.springer.com/article/10.1007/s10584-019-02543-1.
[32] P. Fragkos, K. Fragkiadakis, B. Sovacool, L. Paroussos, Z. Vrontisi, Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union, Energy 237 (2021), 121591.
[33] L. Paroussos, A. Mandel, K. Fragkiadakis, et al., Climate clubs and the macro-economic benefits of international cooperation on climate policy, Nat. Clim. Change 9 (2019) 542–546, https://doi.org/10.1038/s41558-019-0501-1.
[34] F. Polzin, M. Sanders, B. Steffen, et al., The effect of differentiating costs of capital by country and technology on the European energy transition, Climatic Change 167 (2021) 26, https://doi.org/10.1007/s10584-021-03163-4.
[35] P Fragkos, N Tasios, L Paroussos, P Capros, S Tsani. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Pol. 100, 216-226.
[36] P. Fragkos, K. Fragkiadakis, L. Paroussos, R. Pierfederici, S.S. Vishwanathan, Coupling national and global models to explore policy impacts of NDCs, Energy Pol. 118 (2017) 462–473.
[37] M. Roelfsema, H.L. van Soest, M. Harmsen, et al., Taking stock of national climate policies to evaluate implementation of the Paris Agreement, Nat. Commun. 11 (2020) 2096, https://doi.org/10.1038/s41467-020-15414-6.

[38] H.L. van Soest, L. Aleluia Reis, L.B. Baptista, et al., Global roll-out of comprehensive policy measures may aid in bridging emissions gap, Nat. Commun. 12 (2021) 6419, https://doi.org/10.1038/s41467-021-26595-z.
[39] K. Riahi, C. Bertram, D. Huppmann, et al., Cost and attainability of meeting stringent climate targets without overshoot, Nat. Clim. Change 11 (2021) 1063–1069, https://doi.org/10.1038/s41558-021-01215-2.
[40] D. Klenert, et al., Making carbon pricing work for citizens, Nat. Clim. Change 8 (2018) 669–677.
[41] Y. Glemarec, Accelerating and Scaling up Climate Innovation, Green Climate Fund Working Paper No.4, 2021.
[42] S. Rauner, N. Bauer, A. Dirnaichner, et al., Coal-exit health and environmental damage reductions outweigh economic impacts, Nat. Clim. Change 10 (2020) 308–312, https://doi.org/10.1038/s41558-020-0728-x.
[43] IPCC, in: R.K. Pachauri, L.A. Meyer (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, IPCC, Geneva, Switzerland, 2014, p. 151. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.
[44] P. Capros, L. Paroussos, P. Fragkos, S. Tsani, B. Boitier, F. Wagner, S. Busch, G. Resch, M. Blesl, J. Bollen, European decarbonization pathways under alternative technological and policy choices: a multi-model analysis, Energy Strategy Rev. 2 (2014) 231–245, https://doi.org/10.1016/j.esr.2013.12.007.
[45] P. Fragkos, K. Fragkiadakis, Analyzing the macro-economic and employment implications of ambitious mitigation pathways and carbon pricing, Front. Clim. 4 (2022), 785136, https://doi.org/10.3389/fclim.2022.78513.
[46] K. Fragkiadakis, P. Fragkos, L. Paroussos, Low-carbon R&D can boost EU growth and competitiveness, Energies 13 (19) (2020) 5236.
[47] P Fragkos, L Paroussos. Employment creation in EU related to renewables expansion. Appl. Energy 230, 935-945.
[48] D. Gupta, F. Ghersi, S.S. Vishwanathan, A. Garg, Achieving sustainable development in India along low carbon pathways: macroeconomic assessment, World Dev. 123 (2019), https://doi.org/10.1016/j.worlddev.2019.104623.
[49] D. Gupta, F. Ghersi, S.S. Vishwanathan, A. Garg, Macroeconomic assessment of India's development and mitigation pathways, Clim. Pol. 20 (7) (2020) 779–799, https://doi.org/10.1080/14693062.2019.1648235.
[50] OECD, Employment Implications of Green Growth: Linking Jobs, Growth, and Green Policies, Report for the G7 Environment Ministers, 2017. June 2017.
[51] K. Oshiro, et al., Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets, Climatic Change 162 (2020) 1913–1927, https://doi.org/10.1007/s10584-019-02490-x.
[52] Fragkos, Fragkiadakis, Analyzing the Macro-Economic and Employment Implications of Ambitious Mitigation Pathways and Carbon Pricing, 2022.
[53] den Elzen, et al., Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach, Mitig. Adapt. Strategies Glob. Change 27 (2022) 33, https://doi.org/10.1007/s11027-022-10008-7.
[54] A. Garg, P.R. Shukla, S. Parihar, U. Singh, B. Kanakal, Cost-effective architecture of carbon capture and storage (CCS) grid in India, Int. Greenh. Gas Emissions 66 (2017) 129–146.
[55] Coal India Limited. Sustainability Report 2020-21.