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) 12[th] 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).

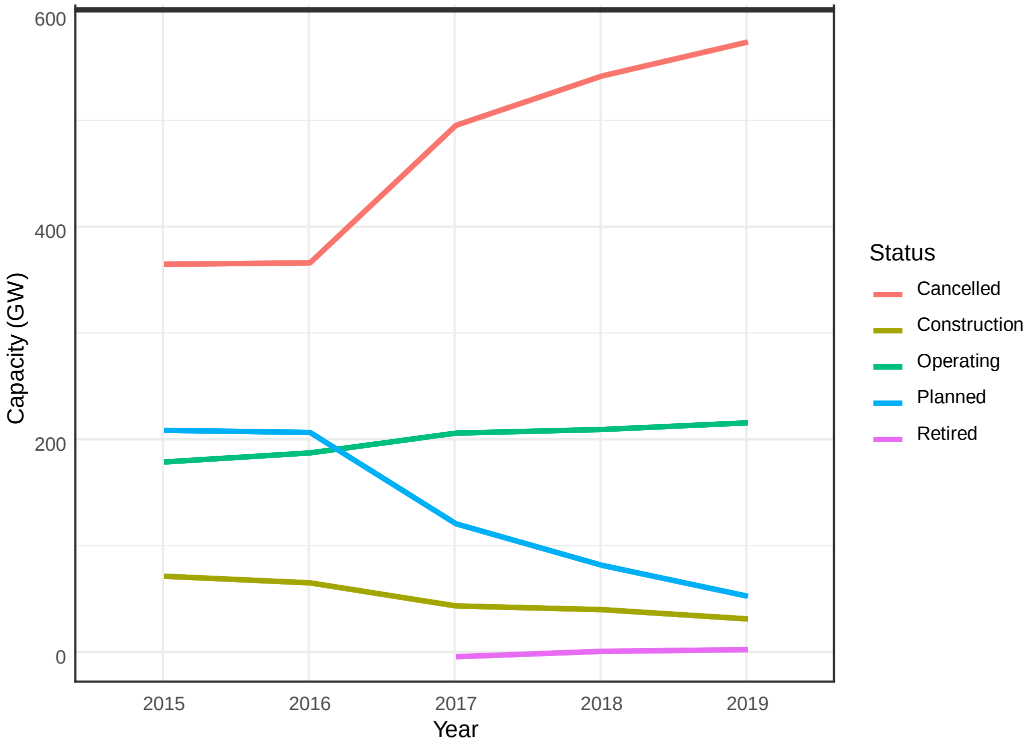


Figure S1 Capacity of unabated coal plants of different status - cancelled (red), under-construction (dark green), operating (green), planned (blue), and retired (pink), with Year. Data from the CoalSwarm Database, 2019.

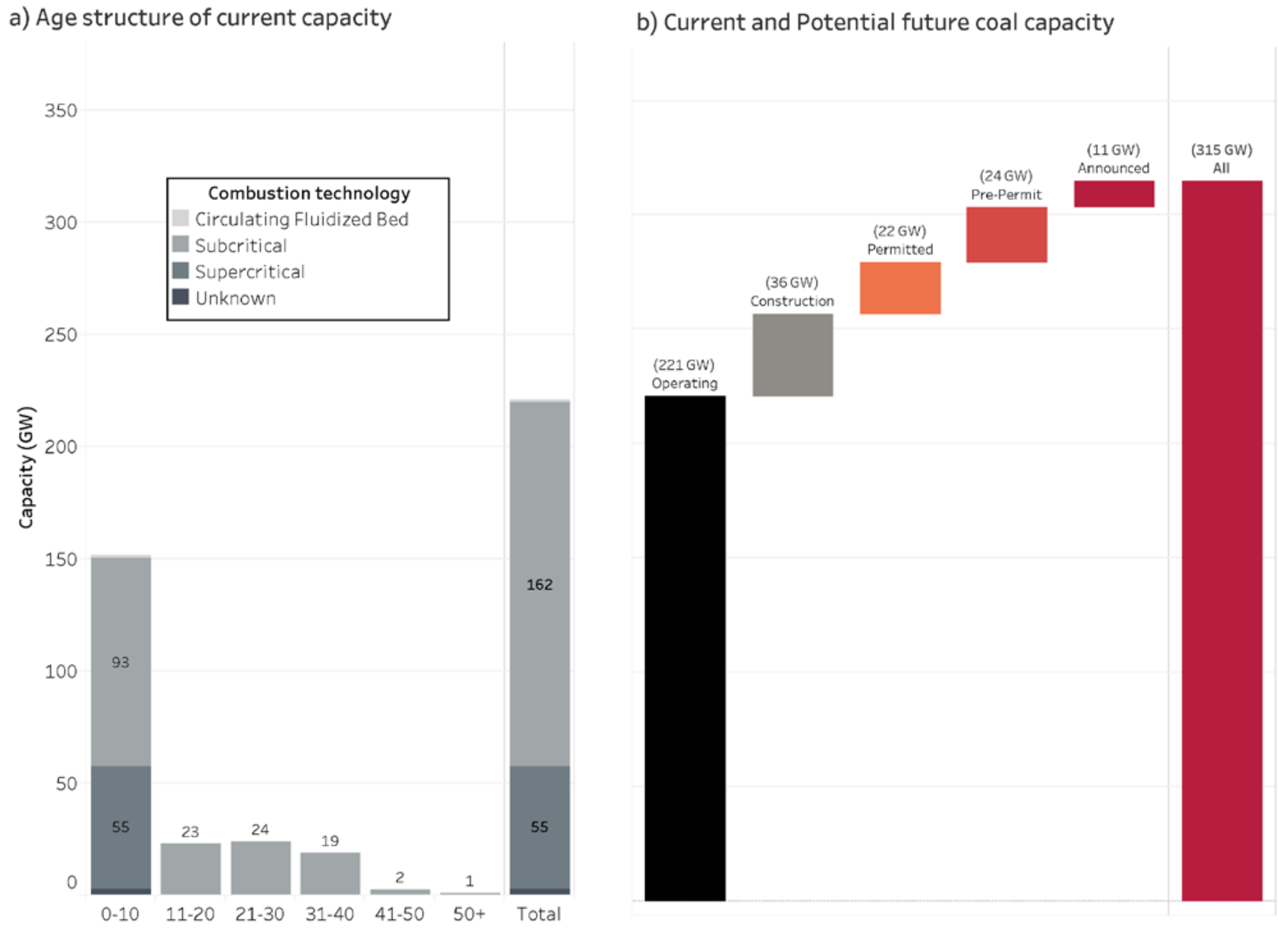
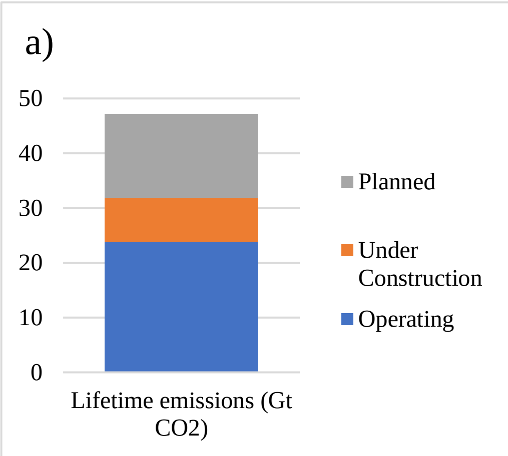


Figure S2 a) Current capacity differentiated on age-group (y-axis) and combustion technology (colour). b) Current and future coal capacity from (Coal Swarm, 2019).

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)



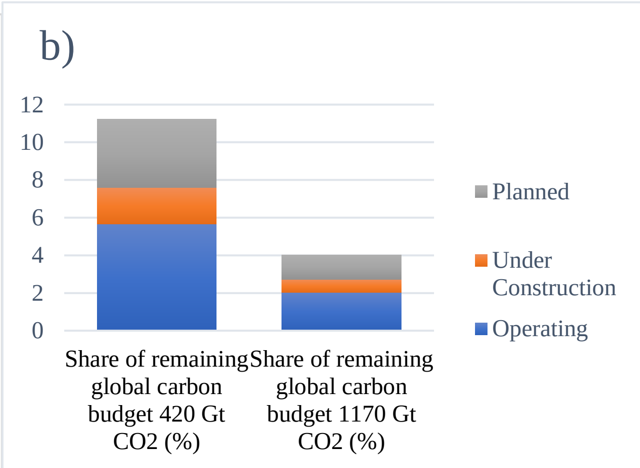


Figure S3 a) Lifetime emissions (in Gt CO2) of different classes of coal plants (operating -blue, under construction - orange, and planned-grey) and b) their share in the remaining global carbon budget (66% chance) for 1.5° C and 2° C (in %). Data from Coal Swarm, 2019. Assuming technical lifetime of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

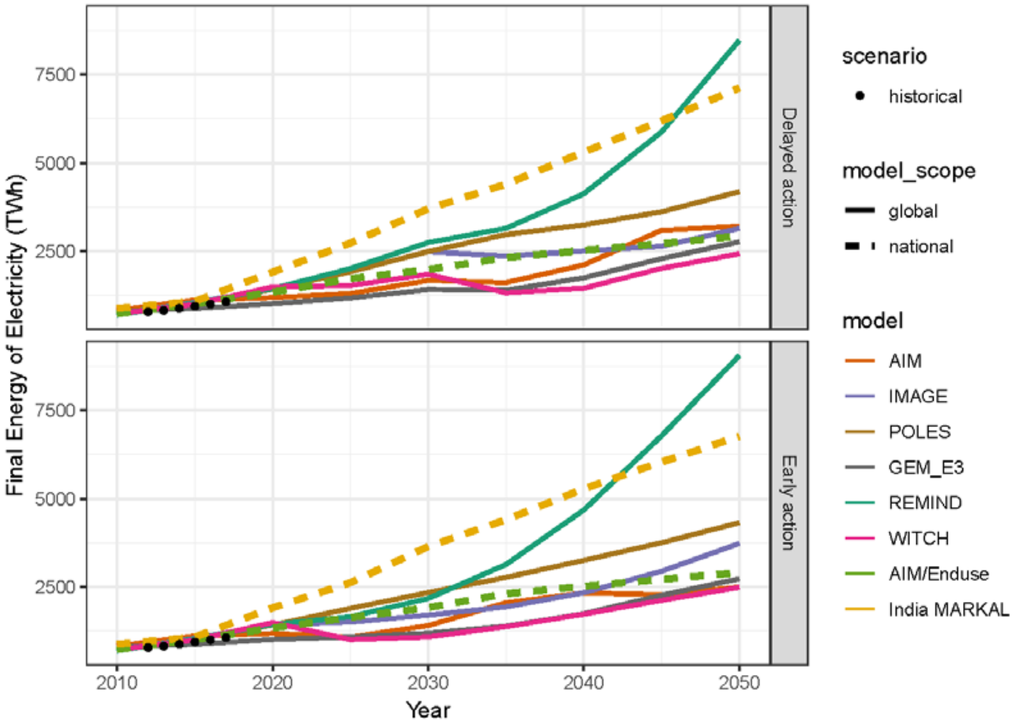


Figure S4 a), b) Final Energy of Electricity in EJ/yr, for the period 2010-2050, for the different national (dashed line) and global models (bold), for the two scenarios – Delayed and Early action.

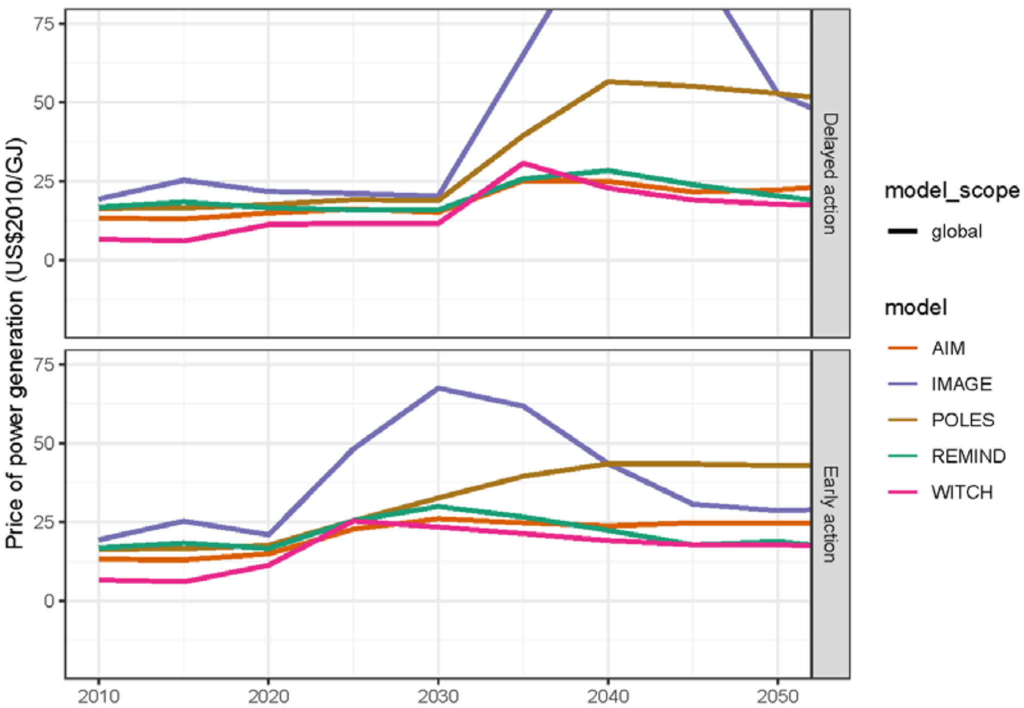


Figure S5 a), b) – Price of power generation (USD2010/GJ) for the Delayed and Early action scenarios from 2010-2050. Results are only for the global models (excluding GEM-E3)

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).

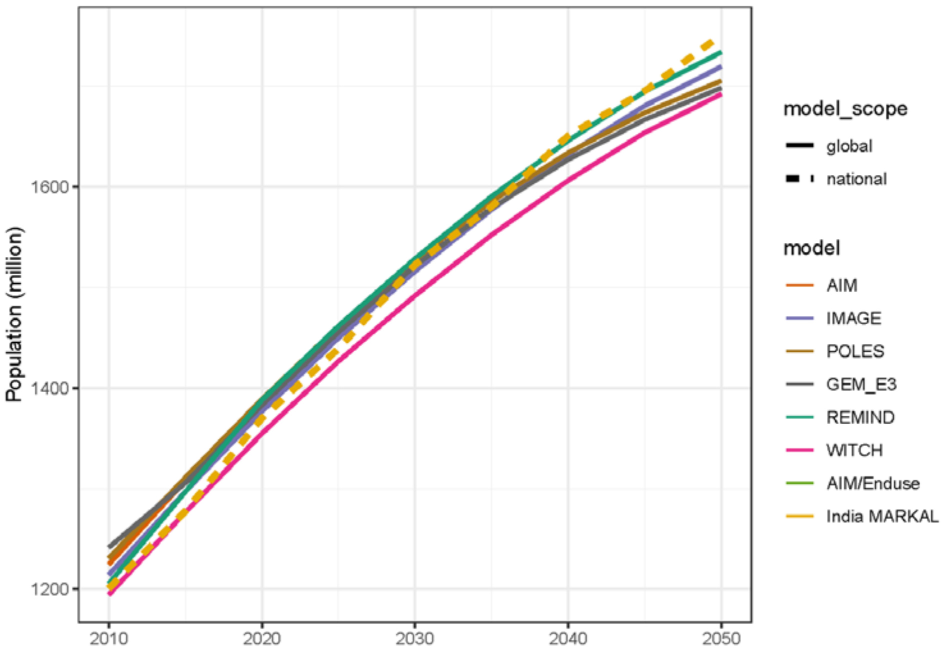


Figure S6 Population (million) in global and national models during the period 2010-2050

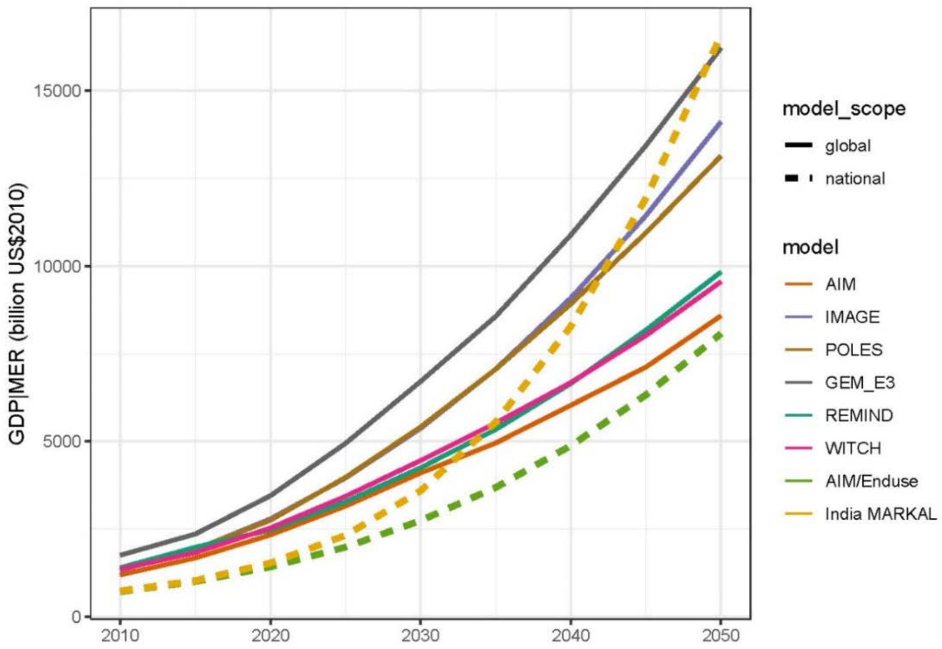


Figure S7 GDP in Market Exchange Rate (USD billion 2010) for different global and national models from 2010 to 2050.

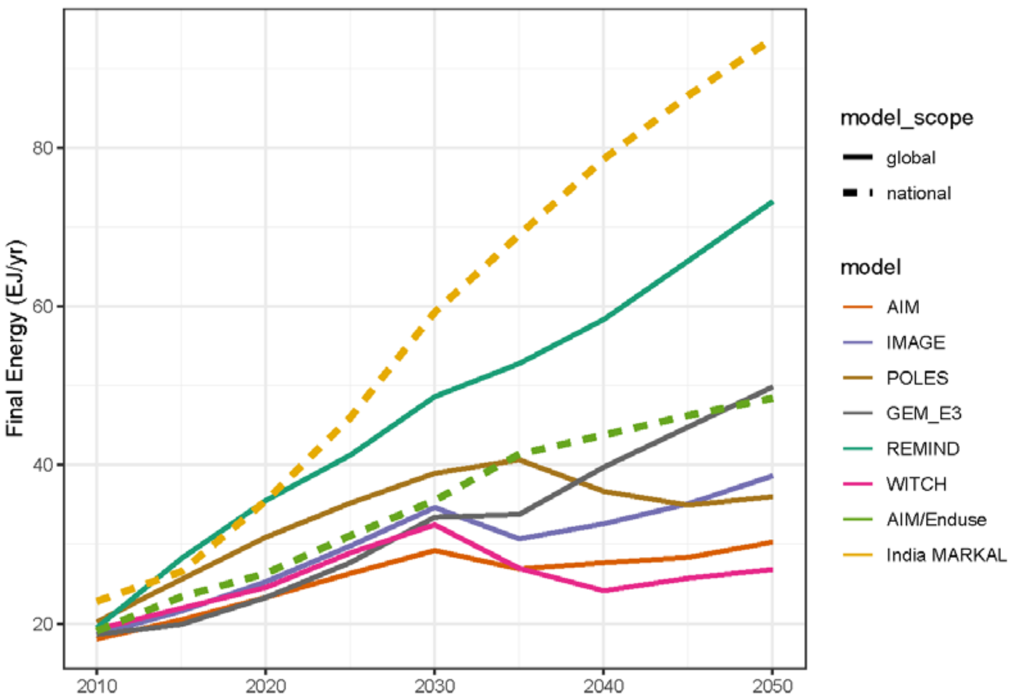


Figure S8 Final Energy demand (EJ/yr) for the delayed action scenario for the different national and global models from 2010 to 2050.

9 Additional Figures

Carbon Price

a) b)

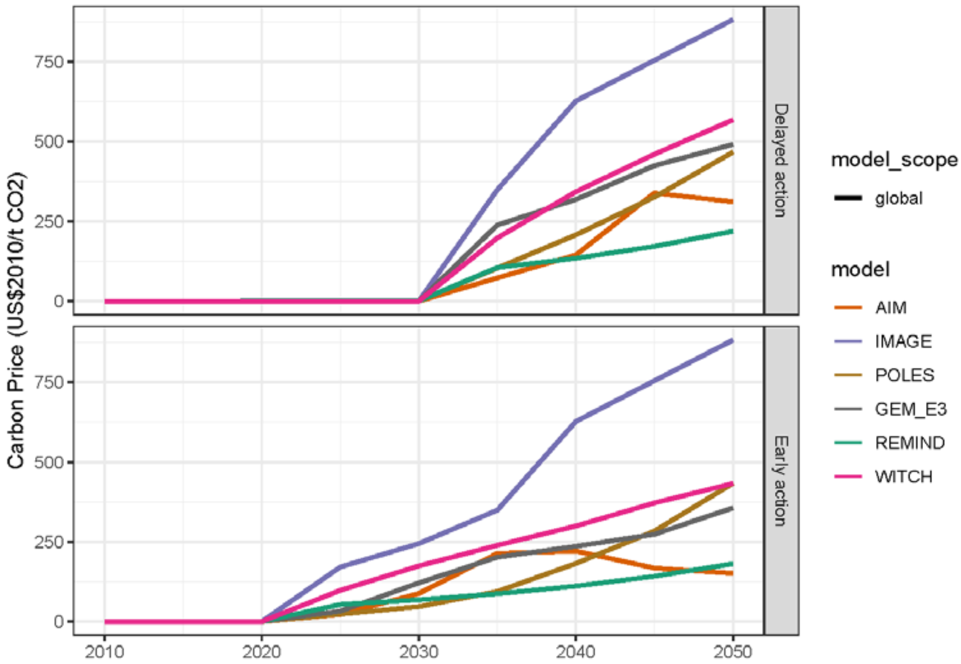


Figure S9 a) b) Carbon Price (in US$2010 per ton of CO2) for the two scenarios- Delayed and Early action. The coloured lines represent different global models

Power generation from coal in Early action

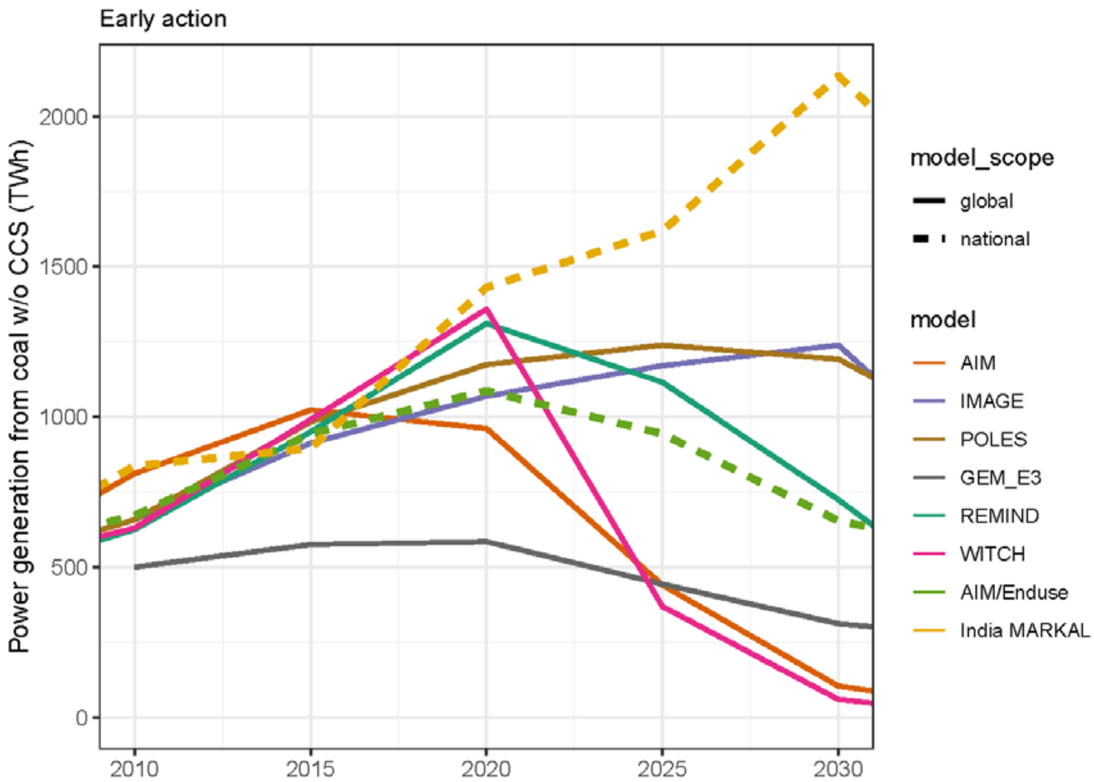


Figure S10: Power generation from coal without CCS in early action scenario (2010-2030). The different colors represent the different models, national models are dashed.

Emissions from energy and electricity sector

a) b) c) d)

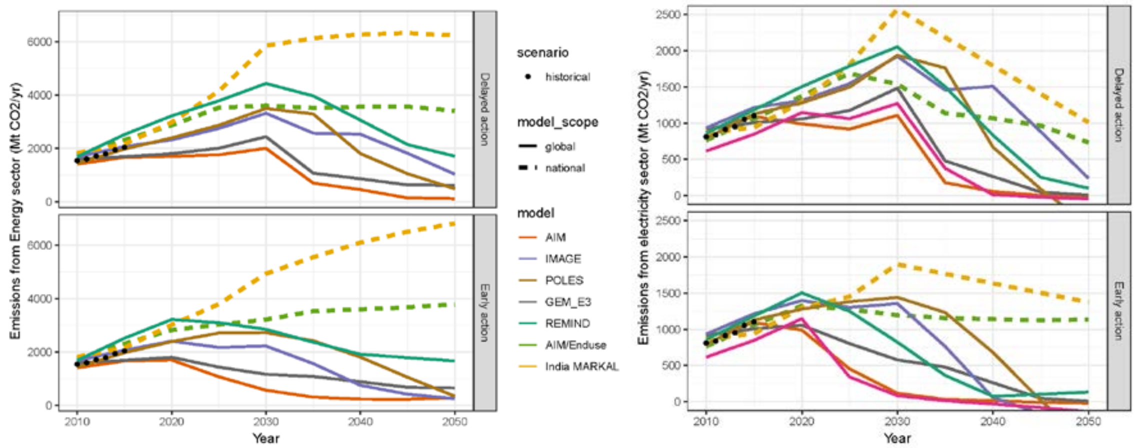


Figure S11 a), b) Emissions from the energy sector (in Mt CO2/yr) , c), d) – emissions from the electricity sector, for the different national and global models for the scenarios – early and delayed action between the period 2010 and 2050. The black dots represent historical values from CDIAC (Carbon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

Cumulative emissions

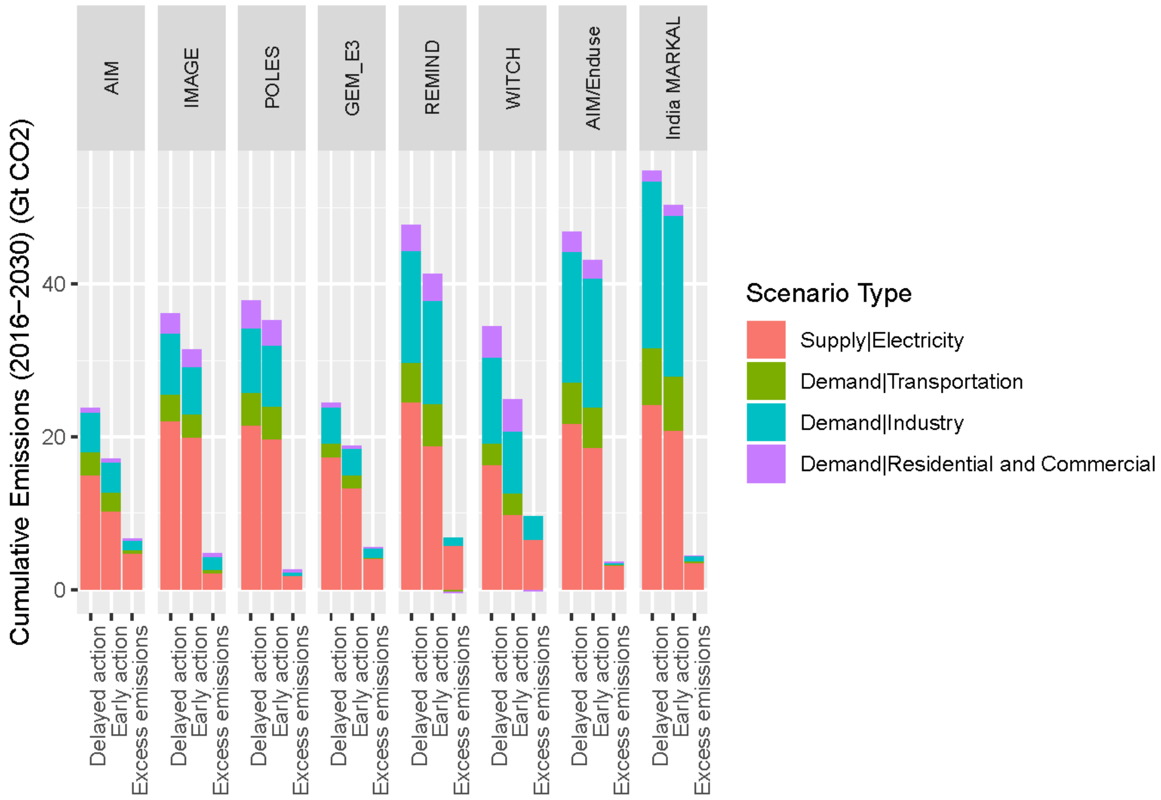


Figure S12 Cumulative emissions categorised according to source - Electricity (red), Transportation (green), Industry (turquoise) and Residential and Commercial (purple), for the different models, for the two scenarios – Early and Delayed action, and the excess emissions due to delayed action.

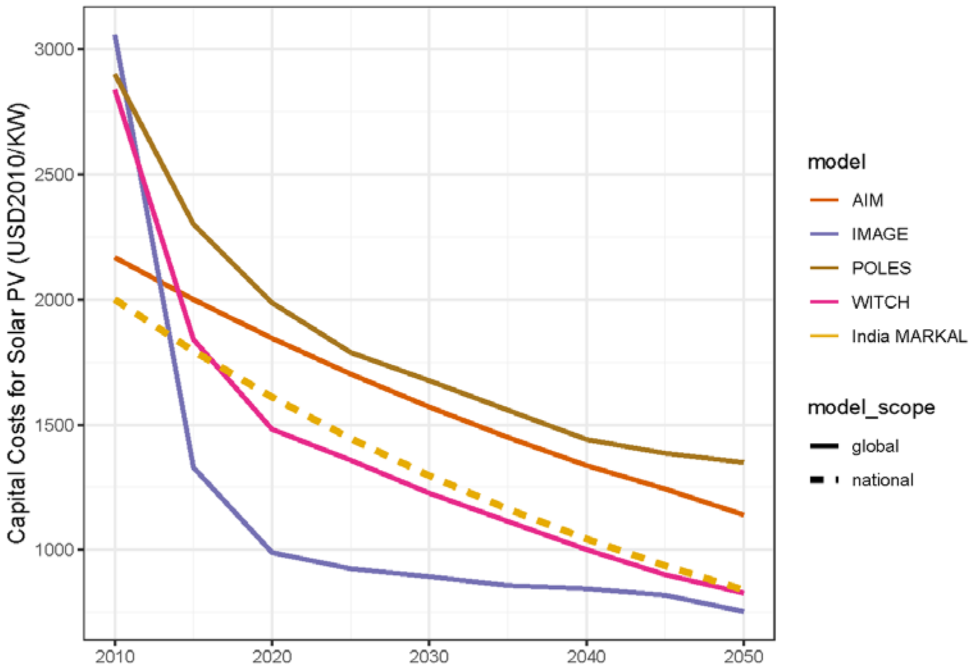


Figure S13 Capital costs for Solar PV (in USD2010/KW) across models. Notre that not all models report this variable.

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)

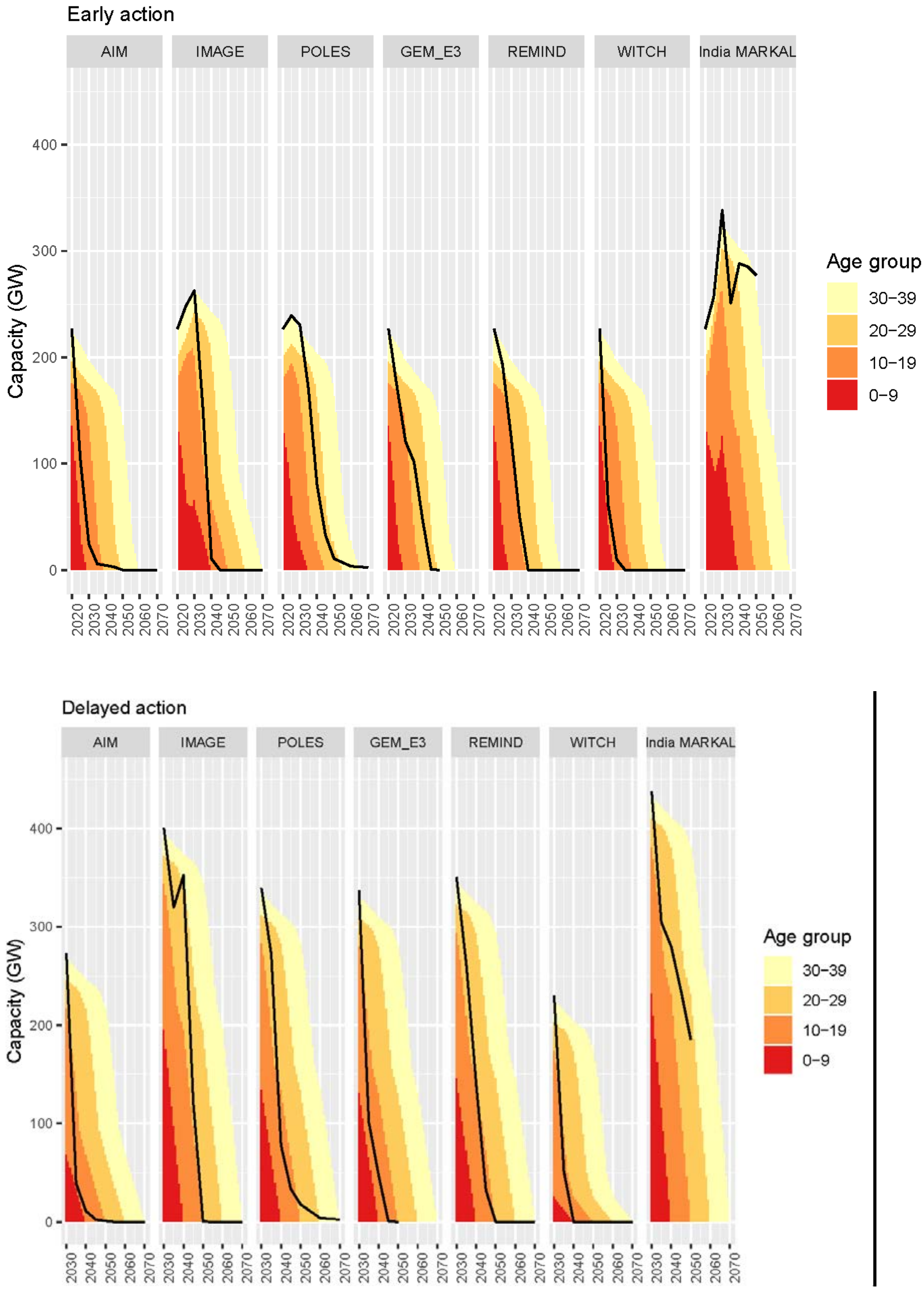


Figure S14 Coal capacity development, assuming natural retirement and colored according to age-group, black lines are model scenario outputs for a) Early action and b) Delayed action

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)

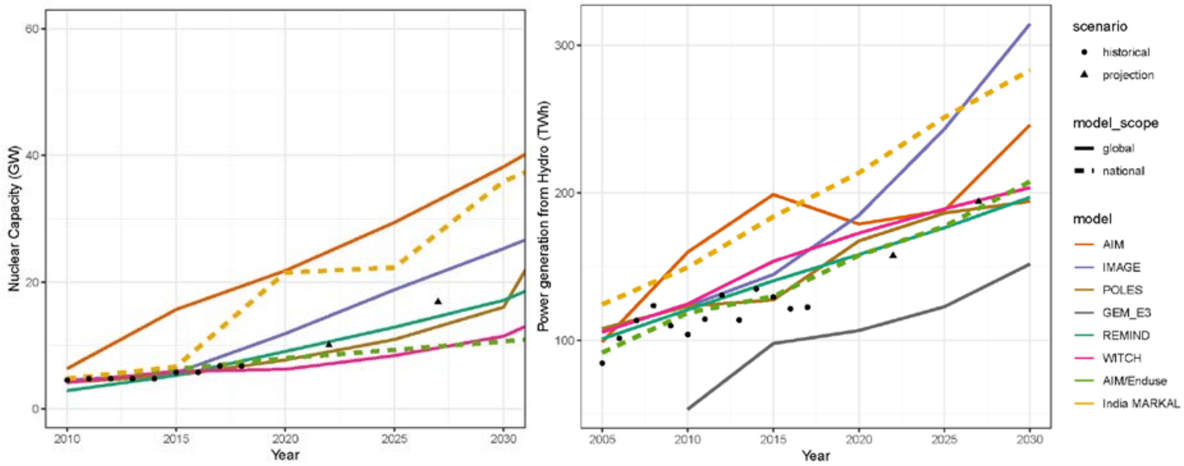


Figure S156(a-b) Projections of Nuclear Capacity (GW) and Power generation from Hydropower (TWh) for the different models under delayed action. Black dots are historical numbers and black triangles are projections, both from the CEA.

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

[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.

References

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