Supplementary Information to ‘A multi-model analysis of long-term emissions and warming implications of current mitigation efforts’

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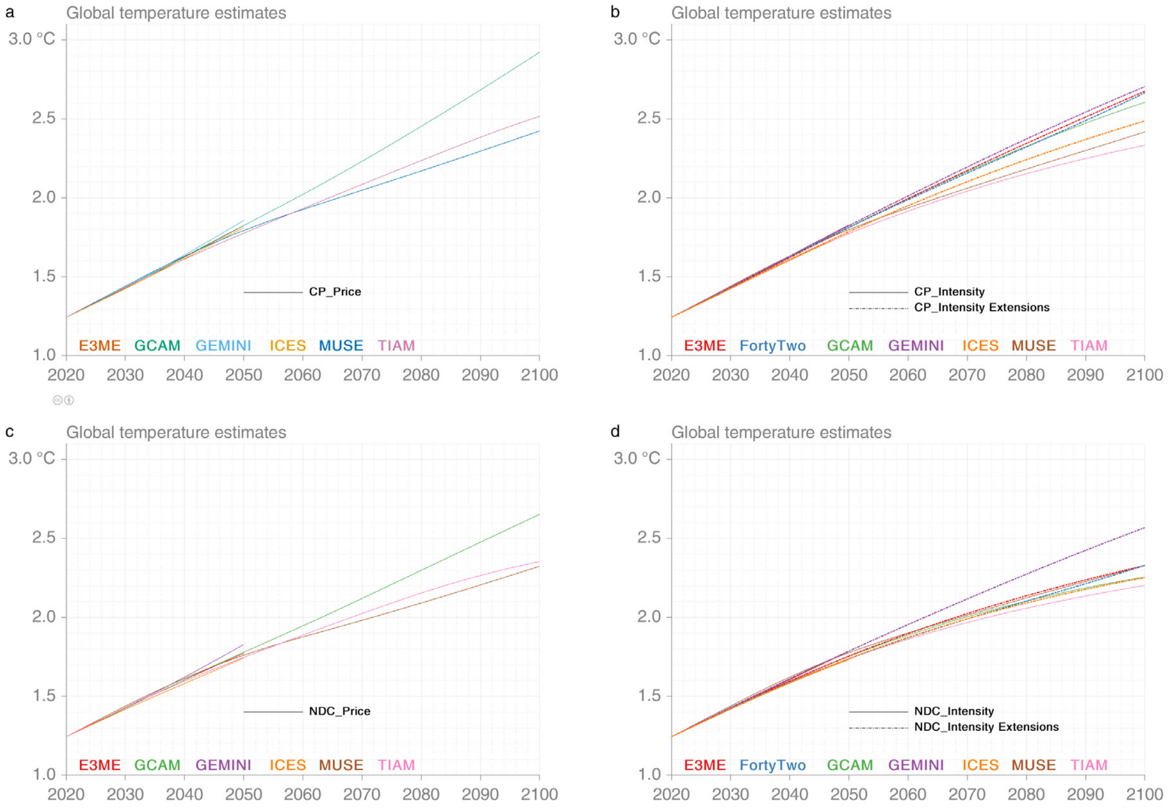

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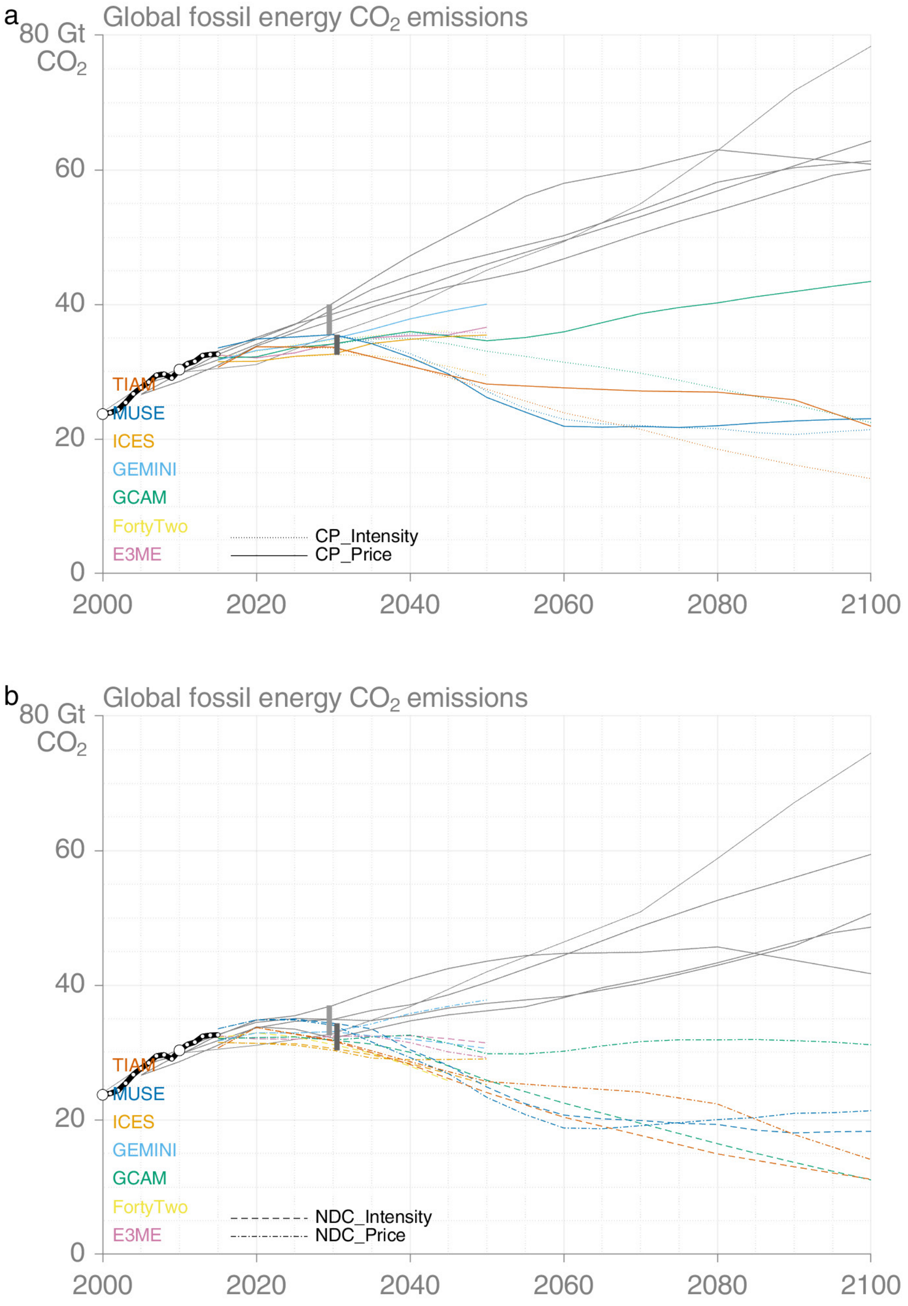

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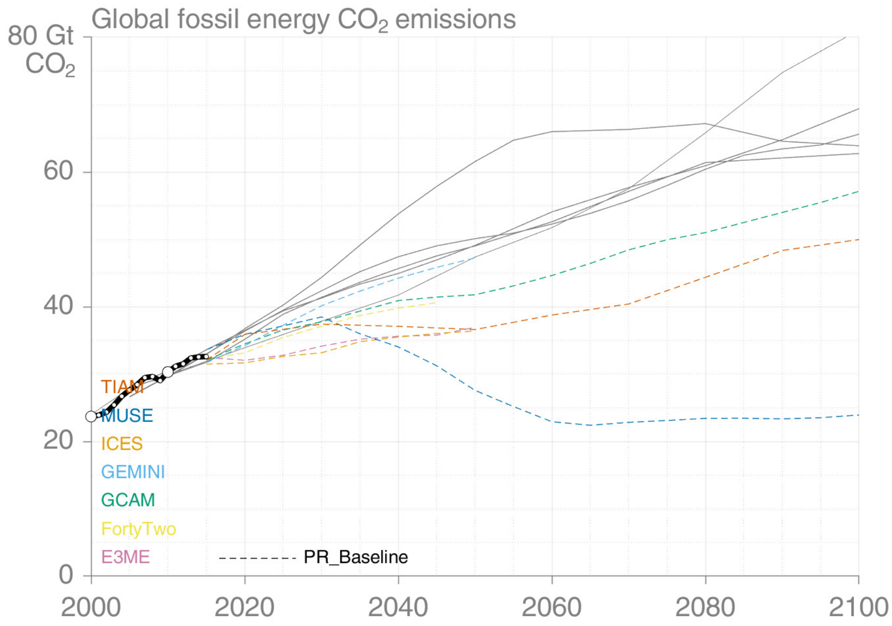

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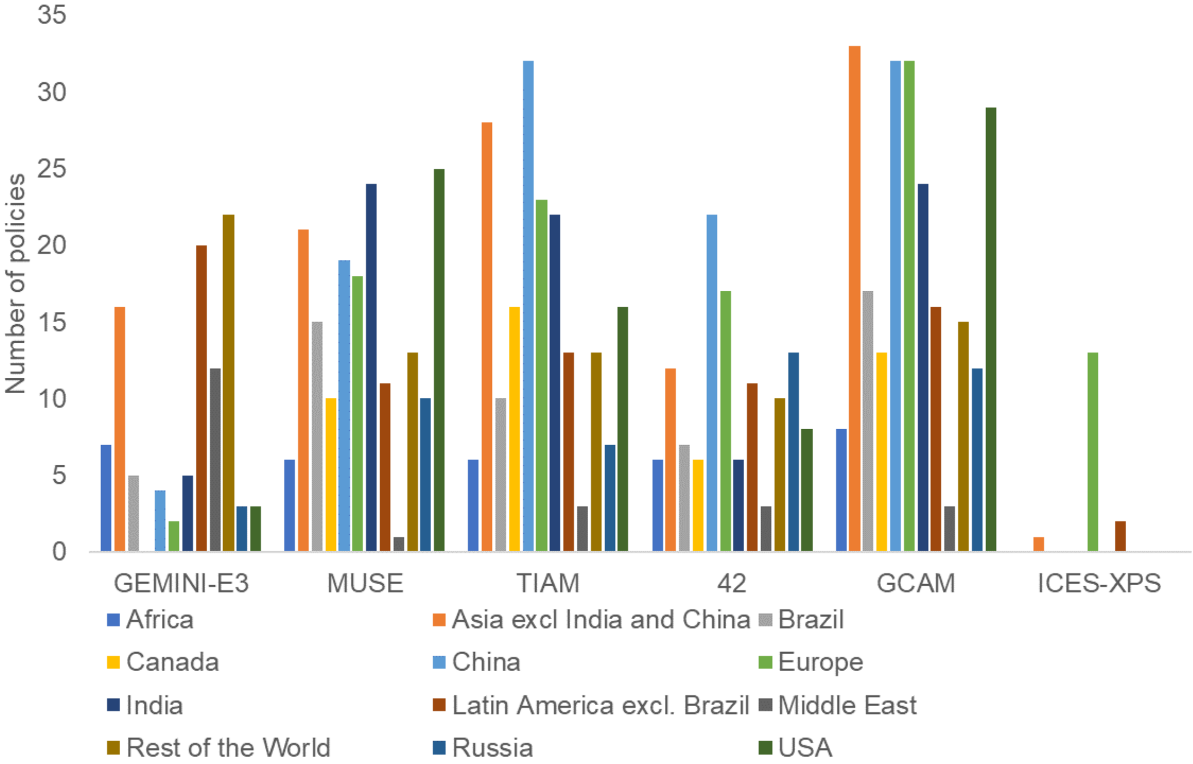

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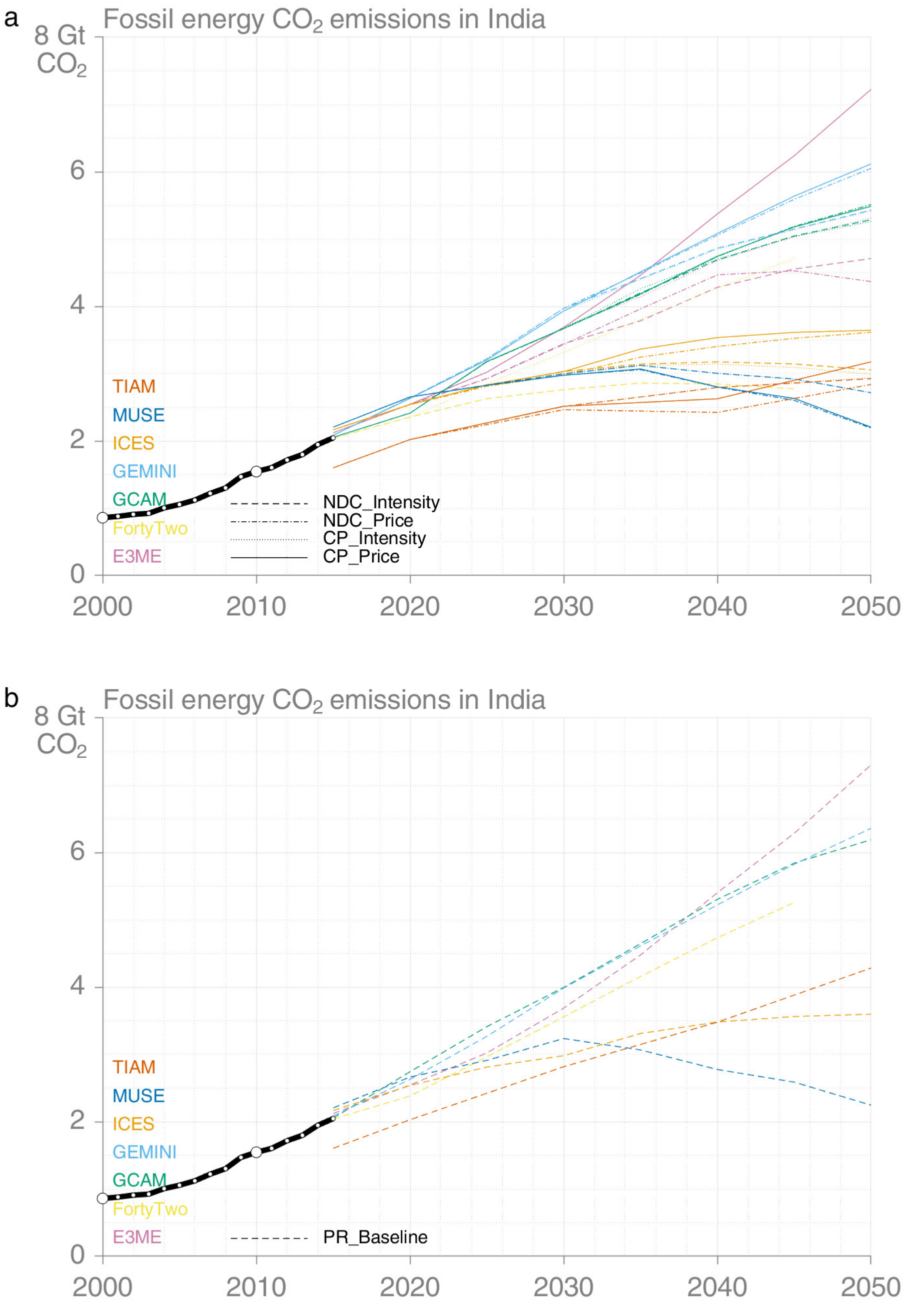

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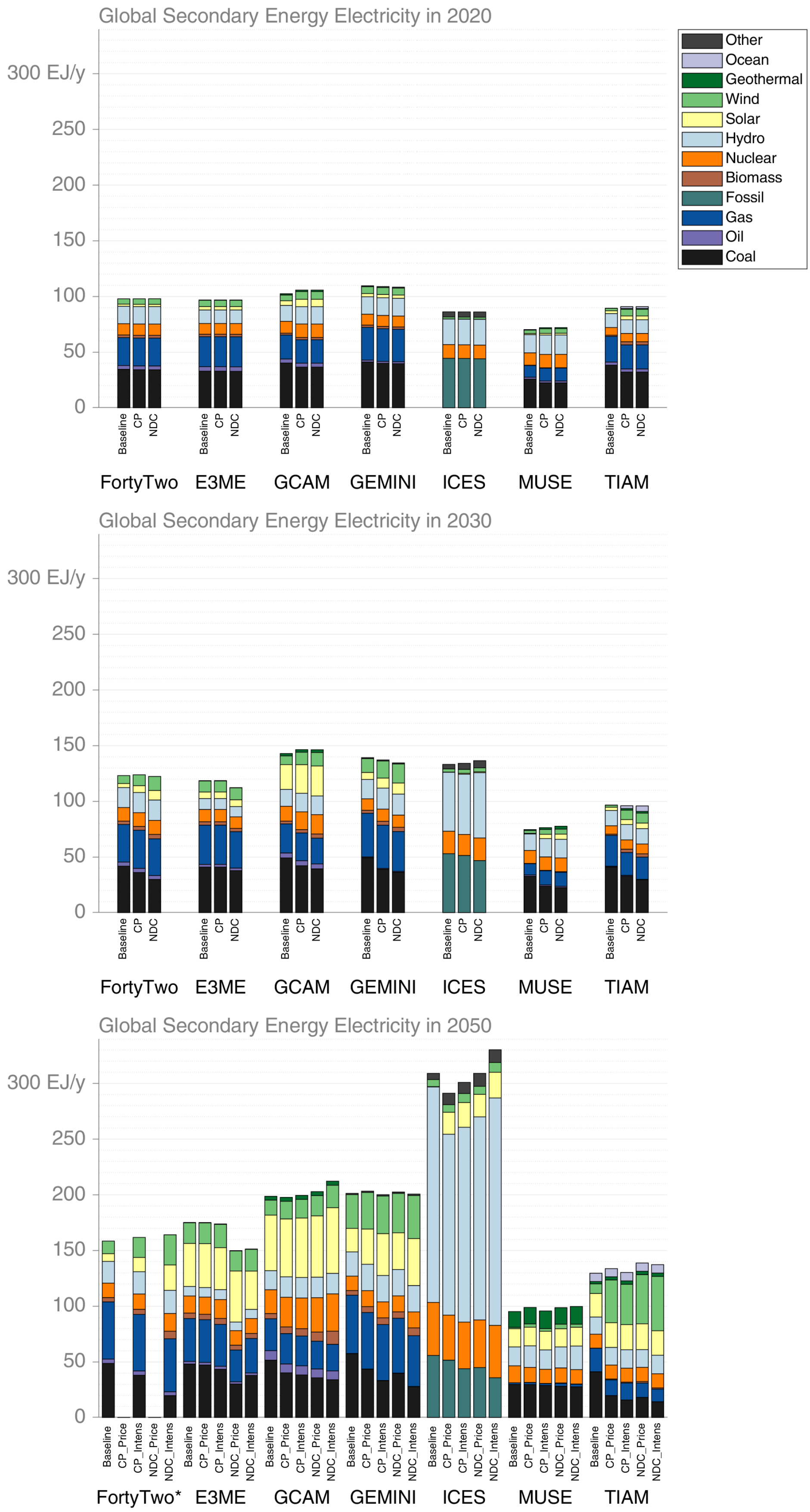

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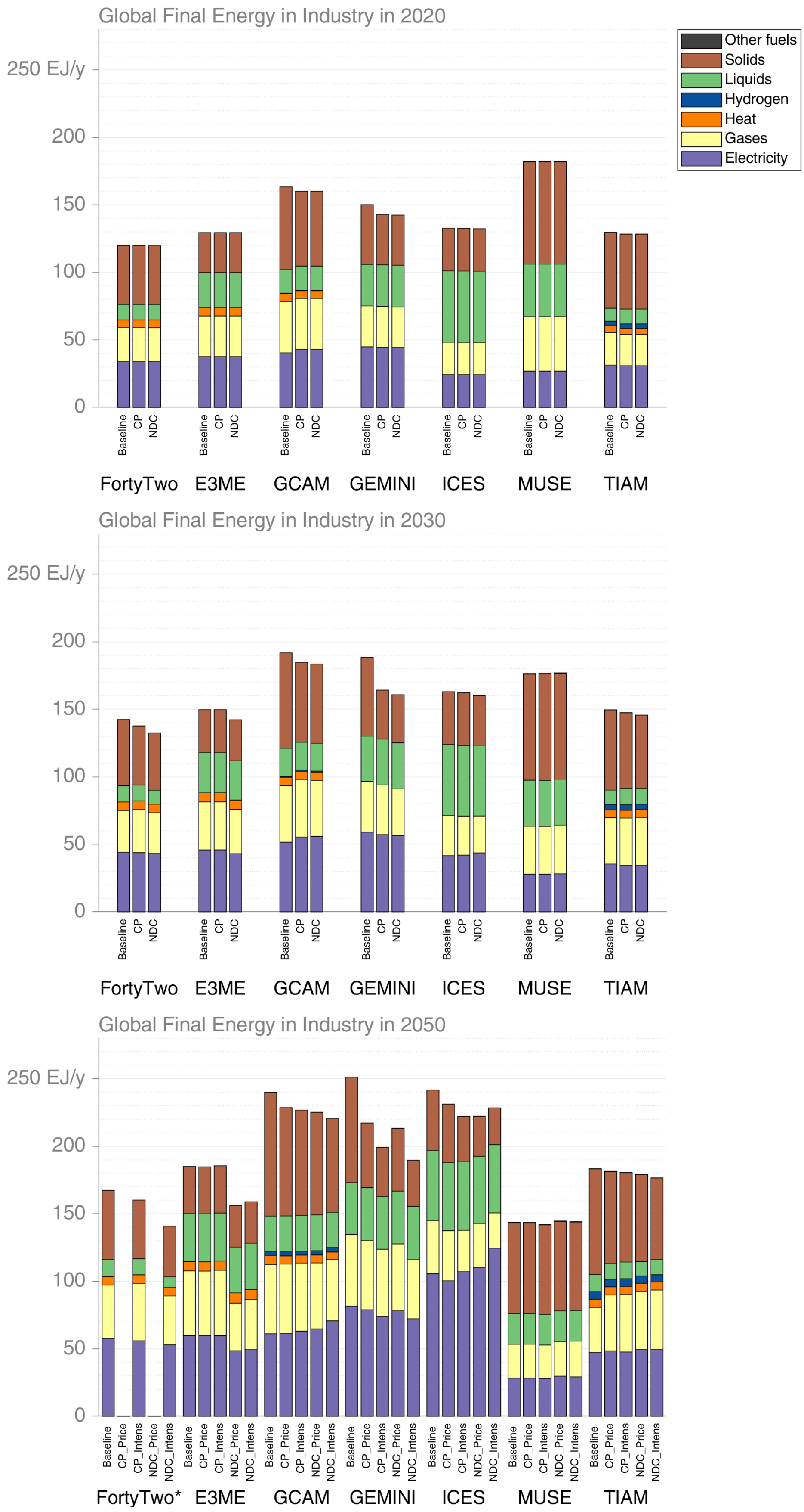
*In 2050, 2045 values are shown for FortyTwo (the end year of the model).



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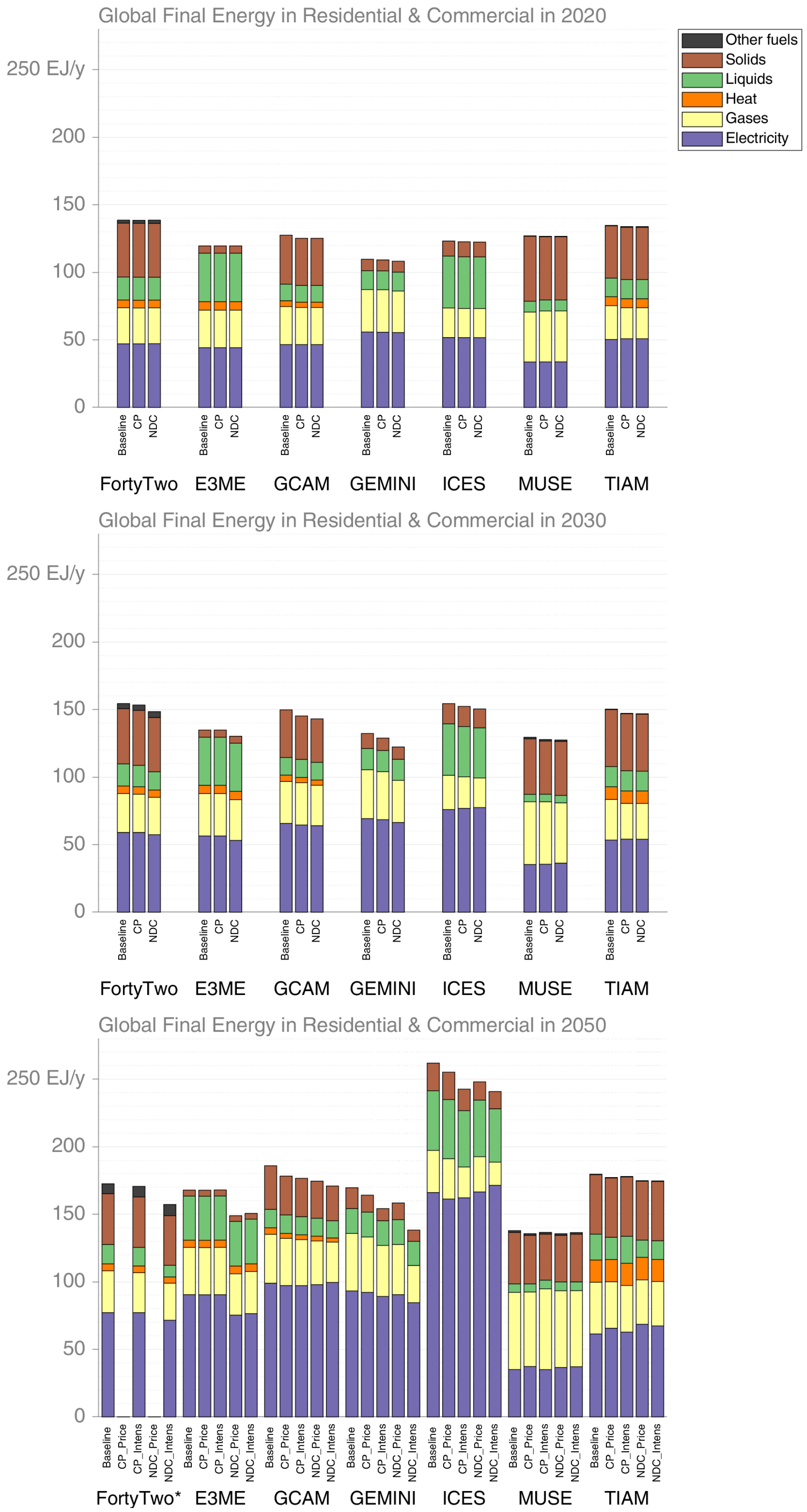

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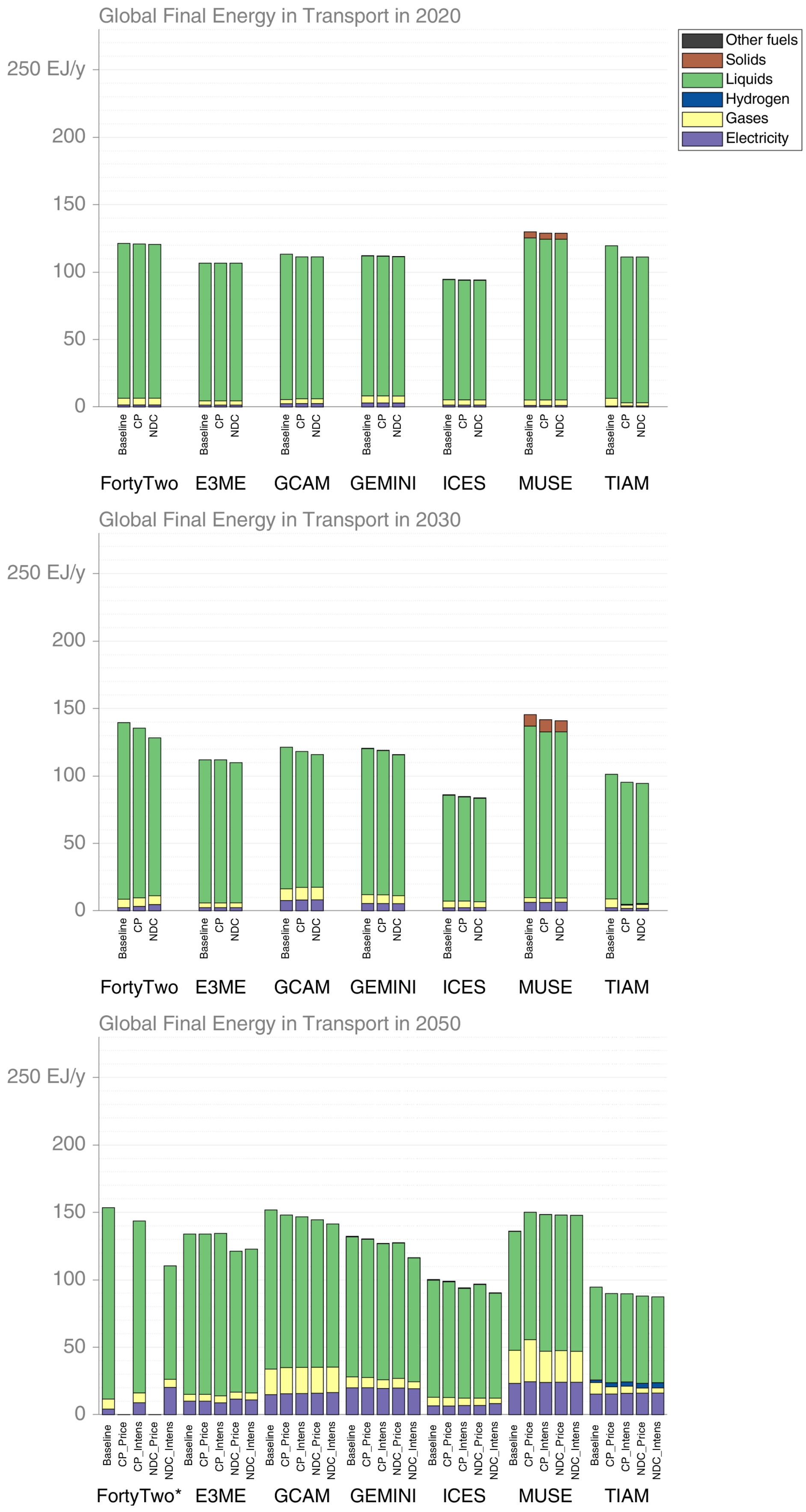

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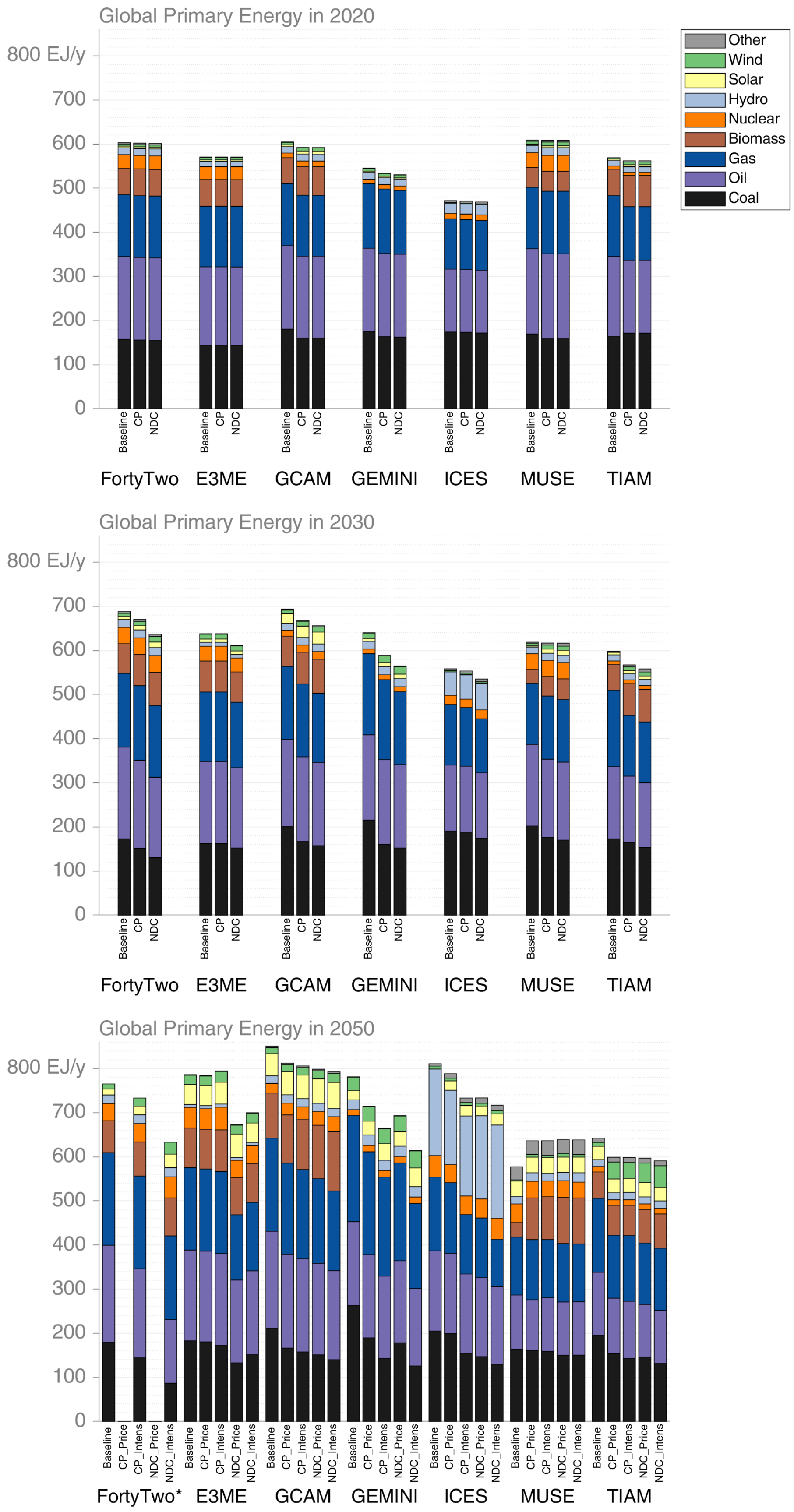

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Supplementary Tables

Model	**World regions**	**Online detailed documentation in I^{2}AM PARIS**
GCAM	32	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/gcam
TIAM	15	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/tiam
MUSE	28	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/muse
FortyTwo	50	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/42
GEMINI-E3	11	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/gemini_e3
ICES	45	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/ices
E3ME	61	http://paris-reinforce.epu.ntua.gr/detailed_model_doc/e3me

Supplementary Table 1 Geographic disaggregation and online model documentation.

Variables	GCAM	TIAM	MUSE	FortyTwo	ICES	GEMINI-E3	E3ME
Population	✓	✓	✓	✓	✓	✓	✓
GDP/total income	✓	✓	✓	✓	✓	✓	✓
Sectoral value added							(✓)
Interest rate							✓
Exchange rates							✓
Electricity generation	✓	✓	✓			✓	(✓)
Road: light duty	✓	✓	✓			(✓)	
Road: heavy duty	✓	✓	✓			(✓)	
Heating	(✓)	✓	(✓)				
Cooling	(✓)	✓	(✓)				
Appliances	(✓)	✓	(✓)				
Process heat	(✓)	✓	✓				
Machine drives & Steam		✓					
CHP	(✓)	✓					
CCS/NETs		✓	✓			✓	
Coal market/import prices					✓	✓	✓
Oil market/import prices					✓	✓	✓
Gas market/import prices					✓	✓	✓
CO_2 emissions	(✓)	✓	(✓)	(✓)	✓	(✓)	(✓)
CH_4 emissions	✓				✓	✓	(✓)
N_2O emissions	✓				✓	✓	(✓)
F-gases	✓				✓	✓	(✓)
Pollutants	✓						(✓)

Supplementary Table 2 Overview of input harmonisation. ✓ means harmonised, (✓) means checked for consistency. For details, including what checked for consistency means, see Supplementary Text 4.

Variable	Time span	Units	Data sources
Population: Total country population	2010-2100	Million people, growth rates	Europe: (European Commission, 2019); Rest of OECD database: short-to-medium term (OECD, 2020); long-term (KC & Lutz, 2017) Rest of the world: estimates up to 2020 (UN, 2019); post-2020 (KC & Lutz, 2017)
Working age Population: Total population between 15 and 64 years old	2010-2100	Million people, growth rates	Europe: (European Commission, 2019); Rest of OECD database: short-to-medium term (OECD, 2020); long-term (KC & Lutz, 2017) Rest of the world: estimates up to 2020 (UN, 2019); post-2020 (KC & Lutz, 2017)
Gross domestic product based on purchasing-power-parity valuation	2010-2100	PPP (constant billion 2010 International $), growth rates	Europe: GDP per capita up to 2070 (European Commission, 2017); GDP per capita post-2070 (Dellink et al., 2017) Rest of OECD database: GDP growth until 2021 (OECD, 2019); short-to-medium term (OECD, 2018); long-term (Dellink et al., 2017) Rest of the world: estimates up to 2020 (IMF, 2019); post-2020 (Dellink et al., 2017)

Supplementary Table 3 Socio-economic assumptions and data sources. See Supplementary Text 4 for details on harmonisation.

Power	Transport	Buildings	Industry
Technologies: renewables (wind, solar, nuclear, geothermal, hydro, and biomass) and non-renewable (coal, gas) technologies	Technologies: cars, buses, and trucks	Technologies: household appliances, lighting, heating and cooling	Technologies: CCS integration
Variables: Costs of investment, fixed and variable operation & maintenance (O&M), capacity factors, conversion efficiencies and technical lifetimes	Variables: Costs of investment, fixed O&M, capacity factors and efficiencies.	Variables: Costs of investment and efficiency ratios between advanced and conventional technologies	Variables: CCS capture rates, CCS energy penalty, and CCS capex increase from the conventional technology
Sources: Napp, Gambhir, Hills, Florin, & Fennell, 2014; Mantzos et al., 2017	Sources: Napp, Gambhir, Hills, Florin, & Fennell, 2014; Mantzos et al., 2017; NREL, 2017	Sources: Mantzos et al., 2017	Sources: Schorcht, Kourti, Scalet, Roudier, & Sancho, 2013; Gardarsdottir et al., 2019;

Supplementary Table 4 Techno-economic assumptions

Supplementary Text

Supplementary Text 1: Current policy and NDC implementation

Nationally Determined Contributions (NDCs) and current policies were implemented at a regional level as ambition to 2030 (the period for which NDCs are most frequently stated and for which current policies' impact can reasonably be projected). Supplementary Data 1 details the current policies implemented in each model and the regional aggregation.

Current policies are implemented according to the database of such policies by region, as detailed in the CD-Links policies database (Roelfsema et al., 2020). The CD-Links database was updated with assumptions on policies from more up-to-date sources for the key emitting regions, notably the IEA policies database (IEA, 2020). The combined database included 340 national and supra-national policies. The models differ in the level of policy implementation due to technological and sectoral granularity, which differs across the models used. A representation of the number of policies implemented in each region by each model is shown in Supplementary Figure 5. Notably, models such as the computable equilibrium ones, like ICES, have their primary strengths at implementing system-level policies such as the European cap and trade system for CO_2 emissions, share of renewables, or carbon tax, but lower capacity to implement technology-oriented fuel efficiency standards.

The scenario protocol (Supplementary Text 2) describes how NDCs in this study are implemented on top of current policies. NDC targets are based on a direct interpretation of countries' *unconditional* Paris Agreement pledges.

Supplementary Text 2: Scenario logic and scenario protocol

This section describes the scenario logic and the protocol for implementing the four main scenarios explored in this study (CP_Price, and CP_Intensity for current policies; NDC_Price, and NDC_Intensity for NDCs) and the 'carbon price only' scenario (CP_PriceOnly) discussed and shown in Figure 5 in the main paper.

Scenario logic

All four scenarios in this study are designed to reflect current levels of mitigation efforts in different world regions, taking current policies as the starting point. Two of the scenarios reflect the efforts implied by current policies (CP) and two of the scenarios reflect additional efforts implied by NDCs (NDC) on top of current policies.

Two methods are used to extend the mitigation efforts implied by current policies and NDCs to 2030 (the period for which NDCs are most frequently stated and for which current policies' impact can reasonably be projected) beyond 2030, resulting in four scenarios in total. Each method represents one way of using common IAM variables to interpret and measure mitigation effort:

- _Price: The carbon prices that, on their own (absent other current policies), achieve (in each region of each model) the same levels of emissions as current policies and NDCs in 2030. We call these carbon prices "equivalent carbon prices" (ECPs).

- _Intensity: The rate of change in emissions intensity of GDP in each region up to 2030.

The two measures of mitigation effort are used to extend regional mitigation efforts beyond 2030 in the following manner:

- _Price: By extending the ECPs in each region, growing at the rate of GDP per capita from 2030 onwards, to represent a “constant” economic burden from carbon pricing, as proxied by the ratio of carbon price to per capita income over time. Fujimori et al. (2016) similarly use constant carbon prices post 2030 to assess the long-term implications of INDCs.
- _Intensity: By keeping the rate of change in emissions intensity of GDP constant after 2030. This method is used by Fawcett et al. (2015) and VanDyck et al. (2016) to assess the long-term implications of INDCs. Cai et al. (2017) explains how emissions intensity targets can be implemented in models with endogenous GDP based on an iterative method.

To increase the realism of how emissions reductions take place in all our scenarios, current policies are represented explicitly both in CP and NDC scenarios, both before and after 2030. After 2030, current policies are assumed to remain in place as “constant” or “minimum” bounds on effort.

Scenario protocol

All scenarios

- Current policies are explicitly represented in CP scenarios and in NDC scenarios both before and after 2030.
- The implementation of current policies after 2030 as “constant” or “minimum” levels depends on the model:
    - For models that have detailed representations of energy systems (MUSE, TIAM, GCAM), current policies are simulated as constraints. For example, where current policies represent the achievement of a minimum share of renewables in power generation, or minimum vehicle efficiency standards, then these policies are kept constant (i.e. a constant minimum share of renewables, or constant minimum vehicle efficiency) beyond 2030. Note that the renewables shares, or vehicle efficiency levels, are not kept constant, but rather at a constant minimum bound—this allows the models to simulate over-achievement against these policy targets, if for example the cost-competitiveness of renewables or more efficient vehicles drives them to do so.
    - For macroeconomic models, such as the computable general equilibrium (CGE) models ICES and GEMINI-E3, policies are more commonly applied as minimum subsidy levels to specific low-carbon technologies, to encourage their take-up. In such cases, these subsidies are held constant in the period beyond 2030, to simulate a continuation of policy support for these technologies.

A graphical illustration of the implementation of CP_Price and NDC_Price scenarios is provided in Extended Data Figure 1. The steps for implementing each scenario are given below.

CP_Price scenarios

1) Implement current policies to 2030. Record emissions in 2030 in all modelled regions.
2) Re-run the model without current policies, using regional economy-wide carbon prices to reach the levels of emissions in 2030 recorded in 1). Depending on the model, the emissions in 2030 can be implemented as caps, allowing the model to find the corresponding carbon prices endogenously. The resulting scenario forms the first part (up to 2030) of the

CP_PriceOnly scenario. The “equivalent carbon prices” (ECPs) in 2030 are the carbon prices that reproduce the emissions caused by current policies to 2030 in each region (i.e. the emissions recorded in 1)).

3) Run the model from 2030 until end (2050 or 2100, depending on model time horizon) with the ECPs growing with GDP per capita in every region. The starting point should be the end point of the scenario run in 2) (not the end point of the scenario run in 1)). Record emissions trajectories (to 2050 or 2100) for all modelled regions. The resulting scenario forms the second part (post 2030) of the CP_PriceOnly scenario.
4) Re-run the model from the beginning, with
    a. Current policies to 2030, kept as constant or minimum levels after 2030.
    b. The emissions trajectories in 3), as regional emissions caps. Depending on the model, the carbon prices needed above current policies in each region to achieve the required emissions reductions may be computed endogenously by the model.

CP_PriceOnly scenarios

CP_PriceOnly scenarios represent intermediate steps in the procedure described above to obtain CP_Price scenarios.

CP_Intensity scenarios

1) Implement current policies to 2030. Record the resulting emissions in every region in the modelled period and compute the annualised rate of change of emissions intensity (emissions per GDP) in every region to 2030.
2) Starting with regional emissions in 2030 recorded in 1), compute regional emissions pathways to the end of the modelling period (2050 or 2100) by applying the annualised rate of change of emissions intensity computed in 1) beyond 2030. This step does not involve running the model.
3) Re-run the model from the beginning, with
    1. Current policies to 2030, kept as constant or minimum levels after 2030.
    2. The emissions trajectories in 2), as regional emissions caps. Depending on the model, the carbon prices needed above current policies in each region to achieve the required emissions reductions may be computed endogenously by the model.

NDC_Price and NDC_Intensity scenarios

Up to 2030, there are two cases:

A. For regions where emissions in CP_Price scenarios are equal to or below NDC targets, NDC_Price scenarios are set equal to CP_Price scenarios.
B. For regions where emissions in CP_Price scenarios are above NDC targets, additional mitigation efforts are implemented in NDC_Price scenarios to ensure NDC targets are met in 2030. Depending on the model, the additional effort can be implemented as an emissions cap on top of current policies, allowing the model to endogenously determine the carbon price needed (in addition to current policies) to reach NDC targets.

Post 2030:

In NDC_Price and NDC_Intensity scenarios, the extension post 2030 is done in the same way as in CP_Price and NDC_Intensity scenarios, the only differences being (in B. cases) the level of emissions in each region in 2030.

Variation across groups

All modelling groups were asked to follow the scenario protocol as closely as possible. In order to ensure the ability to do so, the scenario protocol was designed in a thorough iterative process involving all modelling groups. Individual modifications were made only when model structures meant that this was necessary. In the end, only E3ME, which does not use optimisation and does not compute carbon prices endogenously from emissions caps, had to modify the scenario protocol slightly to fit with model structure. Any model-specific details regarding the specifics of the scenario implementation in different models are given in the individual model descriptions (Supplementary Text 3).

Supplementary Text 3: Model descriptions

Descriptions of each model is provided in this section together with any model-specific notes regarding the implementation of the four scenarios explored in this paper.

For an overview of the regional aggregation and links to the detailed online documentation for each model, see Supplementary Table 1. For an overview of, and comparative assessment across, all seven models included in this study, please see the I^{2}AM PARIS platform (http://paris-reinforce.epu.ntua.gr/overview_comparative_assessment_doc/global).

1. GCAM 5.3Supp

Summary

The Global Change Assessment Model (GCAM) is a global integrated assessment model that represents both human and Earth system dynamics (Edmonds et al., 1994). It explores the behaviour and interactions between the energy system, agriculture and land use, the economy and climate (Calvin et al., 2019). The model allows users to explore what-if scenarios, quantifying the implications of possible future conditions; these outputs are a way of analysing the potential impacts of different assumptions about future conditions.

GCAM reads in external “scenario assumptions” about key drivers (e.g., population, economic activity, technology, and policies) and then assesses the implications of these assumptions on key scientific or decision-relevant outcomes (e.g., commodity prices, energy use, land use, water use, emissions, and concentrations). It is used to explore and map the implications of uncertainty in key input assumptions and parameters into implied distributions of outputs, such as GHG emissions, energy use, energy prices, and trade patterns.

GCAM has been used to produce scenarios for national and international assessments ranging from the very first IPCC scenarios through the present Shared Socioeconomic Pathways (SSPs) (Calvin et al., 2017). Recent use cases include (Markandya et al., 2018), (Huang et al., 2019), and (de Ven et al., 2019).

Economic rationale

The core operating principle for GCAM is that of market equilibrium. The representative agents in the modules use information on prices and make decisions about the allocation of resources. They represent, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents indicate their intended supply and/or demand for goods and services in the markets. GCAM solves for a set of market prices so that supplies and demands are balanced in all these markets across the model; in other words, market equilibrium is assumed to take place in each one of these markets (partial equilibrium), and not in the entire economy across all markets (general equilibrium). The GCAM solution process is the process of iterating on market prices until this equilibrium is reached. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

GCAM is a dynamic recursive model, meaning that decision-makers do not know the future when making a decision today, as opposed to other optimisation models, which assume that agents know the future with certainty when they make decisions. After it solves each period, the model then uses the resulting state of the world, including the consequences of decisions made in that period—such as resource depletion, capital stock retirements and installations, and changes to the landscape—and then moves to the next time step and performs the same exercise. The GCAM version used is typically operated in five-year time steps with 2015 as the final calibration year. However, the model has flexibility to be operated at a different time horizon through user-defined parameters.

Emissions

GCAM uses a global climate carbon-cycle climate module, Hector (Hartin et al., 2015), an open-source, object-oriented, reduced-form global climate carbon-cycle model that represents the most critical global-scale earth system processes. At every time step, emissions from GCAM are passed to Hector, which converts these emissions to concentrations and calculates the associated radiative forcing and the response of the climate system (e.g., temperature, carbon-fluxes, etc.).

Notes on scenario implementation

Energy and land-related current policies have been applied to 16 out of 32 regions, while NDCs have been applied for all regions and covering all GHGs, based on INDC interpretations as provided by (Fawcett et al., 2015), and adapted to the socioeconomic assumptions applied in this paper. In order to avoid discontinuities between the last Current Policies/NDC year (2030) and the first extrapolation year (2035), the extrapolation is only applied to those GHGs that are explicitly constrained by the current policies/NDCs. That means that in the *CP* scenarios extrapolations in all regions are only applied to CO_2 (from energy, industry and LULUCF), while in the *NDC* scenarios extrapolations are only applied to CO_2 in those regions where energy and land-related policies were more restrictive than NDCs, and therefore no additional measures have been used to constrain GHGs on top of the applied policies. This was the case for Argentina, Brazil, China, EU, India, Indonesia, and South-Africa. This does not mean that non-CO_2 gases are not affected in *CP* and partially *NDC* scenarios: energy and land-related policies focusing on CO_2 might indirectly also affect non-CO_2 emissions, and GCAM uses a model-implicit abatement curve for certain industrial and agricultural process emissions, which responds to the sector-wide CO_2 price.

2. TIAM

Summary

The TIMES Integrate Assessment Model, TIAM, is a multi-region, global version of TIMES, which is a modelling platform for local, national or multi-regional energy systems, providing a technology-rich basis for estimating how energy system operations will evolve over a long-term, multiple-period time horizon (Loulou & Labriet, 2008). These energy system operations include the extraction of primary energy such as fossil fuels, the conversion of this primary energy into useful forms (such as electricity, hydrogen, solid heating fuels and liquid transport fuels), and the use of these fuels in a range of energy service applications (vehicular transport, building heating and cooling, and the powering of industrial manufacturing plants). In multi-region versions of the model, fuel trading between regions is also estimated. The TIMES framework is usually applied to the analysis of the entire energy sector but may also be applied to the detailed study of single sectors (e.g. the electricity and district heat sector). The framework can also be used to simulate the mitigation of non-CO_2 greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O). TIAM combines an energy system representation of fifteen different regions.

Recent use cases include (Gambhir et al., 2014), (Napp et al., 2019), and (Realmonte et al., 2019).

Economic rationale

TIAM simultaneously calculates the quantity of production and consumption of the different “commodities” accounted for in the model. These commodities are the different energy forms, the different quantities of deployed technologies, and the different quantities of energy services. The price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity’s price. TIAM operates in a market-clearing manner, such that prices of commodities are consistent with the supply and demand being in balance for all commodities.

TIAM most commonly operates on a perfect foresight principle, such that it has knowledge of all current and future technology costs and fuel supply curves. This allows it to reach a cost-minimising level of commodity production and consumption, which is consistent with meeting all current and future energy demands, as well as any imposed emissions constraints. The total energy system cost (including any losses to consumers’ welfare as a result of energy price rises) is calculated as a Net Present Value (NPV) cost of the energy system over the whole time period until 2100, using a discount factor to value the costs of the energy system at different time points in the future.

Emissions

The climate module in TIAM uses emissions that are calculated within the model, as a result of the energy system’s operations, as well as any mitigation of non-energy CO_2 and non-CO_2 gases. The model tracks the three main sources of GHGs—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). TIAM’s climate module calculates changes in the atmospheric concentration of CO_2, CH_4, and N_2O, and as a consequence the change in atmospheric radiative forcing (which leads to global warming) compared to pre-industrial times, and finally the temperature change over pre-industrial times for the atmosphere and the deep ocean.

Notes on scenario implementation

Non-energy sector’s current policies are not implemented in the *CP* scenarios in TIAM.

3. MUSE

Summary

MUSE is a modelling environment for the assessment of how national or multi-regional energy systems might change over time (García Kerdan, Giarola, et al., 2019). Its scope is the entire energy system, from production of primary resources such as oil or biomass, through conversion of these resources into forms of energy for final consumption, and finally the end-use consumption of that energy to meet economy-wide service demands.

In essence, MUSE is an agent-based framework, in that it explicitly characterises the decision-making process of firms and consumers in the energy system, thereby capturing a variety of features of market imperfection. It is also technology-rich, in that it characterises the cost and performance of each technology option, tracks technology stock, and provides details on investment, operating costs, energy consumption, and emissions with a detailed bottom-up perspective. The agent-based modular structure of the sectors is brought together in a partial equilibrium on the energy system through a market clearing algorithm, which balances supply and demand of each energy commodity. The market clearing algorithm is also able to enforce a carbon budget, which escalates a carbon price until agents in all sectors respond and emissions constraints are met.

MUSE-Global is an implementation of a global model in the MUSE framework, characterising 28 regions of the world, and running over a time horizon of 2010 to 2100. Recent use cases include (García Kerdan, Jalil-Vega, et al., 2019), (Luh et al., 2020), and(Budinis et al., 2020).

Economic rationale

MUSE simulates a microeconomic equilibrium on the energy system. It consists of modular independent agent-based sector modules, joined together by a market clearing algorithm. This algorithm iterates across all sector modules, interchanging price and quantity of each energy commodity in each region, until an equilibrium is reached. It sends commodity prices to the end-use sectors and receives back demand for each of these commodities. These demands are aggregated and sent to conversion (i.e. power systems and refinery) and supply sectors (i.e. extraction of natural gas, coal, oil, renewables, and uranium). Conversion and then supply sectors return the marginal technology levelised cost., which is used to inform an updated price in the market clearing algorithm, whence the procedure iterates again (i.e updated prices are sent to the end-use sectors, etc.). Eventually this process results in a microeconomic equilibrium for each energy commodity in each region. When investigating climate change mitigation, a carbon budget is imposed on each time period. A GHG emissions price is then set in the market clearing algorithm such that the carbon budget is achieved (i.e. by pricing emissions, and thereby incentivising investment in low emissions technology in all sectors via the agent-based modelling described below). The carbon price escalation uses a mix of Newton-Raphson and bisection methods and stops when a convergence criterium is met, typically a relative deviation from the target budget, otherwise it exits the loop when the number of iteration exceeds the limit, and the last iterative value of the carbon price is used for the next simulation periods.

MUSE uses a modular approach and allows to characterise investment decision making specific to each sector and, to produce a more realistic representation of energy system transitions. MUSE uses socioeconomic and firm-level data and analyses to characterise a set of investment decision makers (agents) for each sector. Each sector then applies an agent-based modelling (ABM) approach where “agents” (firms or consumers) apply rules to (a) determine which technologies will be considered for investment; (b) calculate a set of objectives according to their decision-making preferences; and (c) use a method to combine these objectives to make a final investment decision (Sachs et al., 2019). Each of these steps is bespoke, where developers can choose from a set of pre-defined rules or can code and add their own objectives and decision rules. Investment and operational decisions are made in a limited-foresight mode, where imperfect knowledge of future prices and demand is unknown to consumers' and firms; this structure strives to represent the frictions and challenges that could occur as the world aims for systemic technology change to achieve climate change mitigation over the coming eight decades.

Emissions

The achievement of climate change targets in MUSE-Global is dealt with via the imposition of emissions limits on each time period. The model tracks primarily carbon dioxide (CO_2), whereas the remaining sources of GHG emissions, methane (CH_4) and nitrous oxide (N_2O), with different granularity across the sectors. These gases are tracked for each technology, sector, region, and for the world, in each time period.

Notes on scenario implementation

MUSE Global applies by default a global emission trajectory. In this paper, where emissions limits were applied region-by-region the carbon budget approach was solved first for each individual region and then applying a super-loop using the converged carbon prices as price trajectories in a global simulation.

To contain the computation burden, which might result from the starting value of the carbon price and its endogenous step-change, the carbon price can either remain constant or escalate. An endogenous reduction of the carbon price was not envisaged in the algorithm, assuming this approach to best mimic a continuous carbon mitigation effort avoiding technology lock-in exacerbated by the agent-based and limited foresight nature of the model. For this reason, the scenarios were implemented with this principle. In the emissions intensity policy extension, where either binding targets reached within a pre-defined tolerance, or non-binding upper bounds, when the energy system outperforms the emission limit. In the GDP growth extension method, a carbon price equivalent was applied as a price trajectory to estimate the corresponding energy systems emissions.

4. FortyTwo

Summary

FortyTwo is a simulation model for estimating CO_2 emissions associated with energy consumption in a wide range of countries, dividing the world into 50 countries and regions (Shirov et al., 2016). The key goal of the model is to describe the target characteristics of the perspective energy sector in different countries for their effective integration into the global process of regulating emissions. The model is used to calculate the impacts of possible structural changes, as well as of improvements in the efficiency of energy use. The energy sector of all countries is described in detail in the form of energy balances, synchronised with the IEA methodology. Modelling is based on a bottom-up approach: first, the final consumption of energy resources is estimated for the industrial, transport, residential, and services sectors; and then model calculates the necessary amount of primary energy resources needed to produce petroleum products, electricity and heat. Key influencing factors include changes in the fuel structure of electricity and heat production; changes in the efficiency of electricity and heat production based on different types of fuel; changes in the structure of vehicle fleet (for cars and trucks); changes in energy consumption per capita; and changes in energy efficiency in manufacturing sectors of the economy.

The forecast period is until 2045, while energy balances of all countries are built for each year (i.e. yearly time steps).

Economic rationale

Modelling is based on a bottom-up approach: first, the final consumption of energy resources is estimated for industry, transport, the residential sector, and services; and then the model calculates the necessary amount of primary energy resources needed to produce petroleum products, electricity, and heat. The amount of primary energy consumption in these two phases explains the total energy consumption, which is multiplied by the carbon intensity vector and thus CO_2 emissions associated with the energy sector are calculated.

The process of energy consumption is modelled as a combination of three classes of influencing factors: a gross factor characterising the size of an object consuming energy (GDP, population, vehicle fleet, electricity production, etc.), a structural factor determining which part of an object consumes a particular energy product (structure of GDP, electricity mix, and vehicle synthesis), and a technological factor describing the dynamics of consumption (fuel efficiency, power generation efficiency, and energy intensity of value added per sector).

Emissions

FortyTwo does not have a climate module and does not calculate the impact of anthropogenic emissions on climate change. The current version of the model tracks only carbon dioxide (CO_2) emissions.

Notes on scenario implementation

In respect to the scenario protocol of this study, FortyTwo could not implement the CarbonPrice (_*Price*) scenarios because the model does not support a carbon price.

5. GEMINI-E3 7.0

Summary

The General Equilibrium Model of International-National Interactions between Economy, Energy, and the Environment (GEMINI-E3) is a multi-country, multi-sectors, and a recursive computable general equilibrium (CGE) model (Bernard & Vielle, 2008). GEMINI-E3 simulates all relevant domestic and international markets, which are assumed to be perfectly competitive. It implies that the corresponding prices are flexible for commodities (through relative prices), for labour (through wages), and for domestic and international savings (through rates of interest and exchange rates). Time periods are linked through endogenous real interest rates from balancing of savings and the investment. It follows, real exchange rates are endogenously determined by constraining foreign trade deficits or surpluses. These rates link the national and regional scope in the model.

There is one notable, yet usual exception to this general assumption of perfect competition. It relates to foreign trade, where goods of the same sector produced by different countries are not supposed to be perfectly competitive. They are considered as economically different goods, more or less substitute according to the Armington elasticity of substitution. Simulations with GEMINI-E3 result in outputs on a regional and annual basis. These include carbon taxes, marginal abatement costs, prices and net sales of tradable permits, and effective abatement of CO_2 emissions. The model also projects the total net welfare loss and its components (e.g. net loss from terms of trade, pure deadweight loss of taxation, and net purchases of tradable permits), macro-economic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and data at the industrial level (e.g. change in production and in factors of production, and prices of goods).

GEMINI-E3 is available in several versions with different sectors and regions classifications depending on the research question studied. For example, analysing the European burden sharing requires disaggregation of the 28 European member states individually, and the European version is used (see(Vielle, 2020); and (Babonneau et al., 2020)). In this paper, the world economy is divided into five countries (USA, China, India, Brazil, and Russia) and six aggregated regions, including EU-28. The analysis is based on GTAP-10 (Aguiar et al., 2019), a database that accommodates a consistent representation of energy markets in physical units (tons of oil equivalent) and detailed socio-accounting matrices in USD for a large set of countries or regions and bilateral trade flows. Recent analytical studies include (Babonneau et al., 2018), (Vielle, 2020), and (Babonneau et al., 2020).

Economic rationale

For each sector and region, GEMINI-E3 computes total demand as the sum of final demand (investment, consumption, and exports) and intermediate consumptions by all sectors. Then, demand is split between imports and domestic production according to the Armington assumption. Domestic production technologies are described through nested Constant Elasticity of Substitution (CES) functions, which differ by sector.

Household behaviour consists of three interdependent decisions: labour supply; savings; and consumption of various goods and services. Both labour supply and the rate of savings are assumed to be exogenous. Demand in the different commodities has consumption prices and “spent” income (i.e. income after savings) that is derived from nested CES utility functions. At the first level of the consumption function, households choose between three aggregates: housing, transport, and other consumptions. Energy consumption is split for transportation and housing purposes, while transport demand is classified into purchased and own transports. The model distinguishes three types of personal vehicles depending on the fuel used. These include electric vehicles, which are mainly dedicated to short or medium distance, and two other types using the same motorisation (i.e. internal combustion using petroleum products, and the other biofuels). Each vehicle is characterised by a vehicle capital and a type of fuel used (refined oil, biofuel, or electricity).

Total government consumption is exogenous. Its level changes over time as it is driven by the growth rates of the main aggregates of the economy. The model splits total consumption between goods, based on fixed budget shares. The exports are the sum of imports by all other countries/regions that are endogenously determined in the model. Investment by products is derived from investment by sectors through a transfer matrix. Sectoral investment is determined from an "anticipated" capital demand using the CES function of each sector. Anticipated production prices and demands are based on adaptive expectations.

The government surplus or deficit is the difference between revenues accruing from taxation (direct and indirect, including social security contributions) and two types of expenditures (public consumption and transfers to households such as social benefits).

Emissions

GEMINI-E3 computes all GHG emissions included in the Kyoto basket: CO_2, CH_4, N_2O and fluorinated gases. Carbon emissions are directly computed from fossil energy consumption in physical quantities using coefficient factors that differ among firms (i.e. sectors), households, and regions. For non-CO_2 GHG gases, the emissions of each source are linked to an activity level (or an economic driver).

Notes on scenario implementation

All policies included in the *CP* scenario have been translated into targets, which are implemented through taxes and subsidies. The Russian policies aiming to decrease the coal share in total primary energy supply, for instance, are implemented by taxing coal consumption. In case of policies linked to the deployment of renewable electricity generation, these are implemented through a subsidy on renewable electricity generation. For aggregated regions (such as Africa), policies were detailed at the national level and aggregated by considering their respective contribution in the region (e.g. the renewable target in electricity for Africa is a weighted average of each national policy).

Some policies related to energy efficiency improvement are difficult to implement in the model due to lack of sufficient technological granularity. For post-2030 mitigation efforts, a carbon price was introduced in each country/region and applied on all GHG emissions (CO_2, CH_4, N_2O and fluorinated gases) excluding LULUCF.

6. ICES-XPS 1.0

Summary

The Intertemporal Computable Equilibrium System (ICES) is a recursive-dynamic multi-regional Computable General Equilibrium (CGE) model developed to assess economy-wide impacts of climate change on the economic system and to study mitigation and adaptation policies. The model's general equilibrium structure allows for the analysis of market flows within each national economy and international flows with the rest of the world. This implies going beyond the "simple" quantification of direct costs of a shock/policy, to offer an economic evaluation of second and higher-order effects within specific scenarios of climate change, climate policies and/or different trade and public-policy reforms in the vein of conventional CGE theory.

Model behavioural equations derives from GTAP-E model (Burniaux & Truong, 2002) and are characterised by recursive dynamic features, i.e. the model finds a new general (worldwide and economy-wide) equilibrium in each period (Eboli et al., 2010). The ICES-XPS 1.0 version of the model introduces a more detailed representation of government behaviour splitting the usual regional household into two agents (i.e. government and private household) and characterising them with different behavioural equations (Parrado et al., 2020).

ICES-XPS equations are connected to the GTAP 9 POWER database (Aguiar et al., 2016), which accounts for all real economic flows of the world economy and in addition offers a disaggregated representation of the electricity sector (Peters, 2016). The ICES database has been further extended following model developments regarding the public sector (Parrado et al., 2020). In addition to government revenues and expenditures already included in the GTAP 9 database, other monetary flows have been made explicit: international transactions among governments (i.e. foreign aid and grants) and transactions between the government and the representative private household (i.e.net social transfers, interest payment on public debt to residents), flows among governments and foreign private households (i.e. interest payment on public debt to non-residents), and public debt.

The model is linked to the Aggregated Sustainable Development goal Index (ASDI) module that generates scenario and policy specific projections up to 2030 (2050) of selected SDG indicators allowing to assess the systemic implication of implementing a policy on countries' sustainability. In order to perform a sustainability analysis, the GTAP database has been further integrated with international statistics in order to single out the following sectors: Research and Development (R&D), Education, and Health.

Recent use cases include (Campagnolo & Davide, 2019), (Parrado et al., 2020), and (Campagnolo & Cian, 2020).

Economic rationale

The CGE framework makes it possible to account for economic interactions of agents and markets within each country (production and consumption) and across countries (international trade). Within each country the economy is characterised by multiple industries, a representative household, and the government. Industries are modelled as representative, cost-minimising firms, taking input prices as given. In turn, output prices are given by average production costs.

For each productive sector, a typical firm maximises its profits given a set of input (factors and intermediate inputs) and output prices. This means that factor remuneration equals their marginal costs based on endogenous relative prices. Consistent with neoclassical theory, the production technology assumes constant returns to scale. Each commodity is sold domestically or abroad without any substitution degree. However, following the Armington approach, productive sectors and final institutional accounts purchase a composite of not-perfectly substitutable domestic and foreign commodities.

The representative household earns most of its income from the returns of owned primary factors (capital, labour, land, and natural resources). In addition, the household is taxed and receives transfers from the government and the rest of the world (i.e. interest repayments). Then, income is split between consumption and saving in fixed shares.

Government income derives mainly from direct and indirect taxes, but a small fraction comes from transfers from other governments (i.e. grants). The difference between revenues and expenditures is the budget deficit, which is primarily financed through borrowing (or dissaving) from the capital market. Both government and private consumers' savings are collected in a regional saving pool, which accrues to the supra-national Global bank, which redistributes sources for investments. Then, the Global Bank allocates investments to regions according to GDP and differentials in rates of return.

ICES- XPS is solved as a series of equilibriums. The dynamic of the model is led by two accumulation processes for capital and government debt. Capital accumulation is modelled endogenously, with current-period investment generating new capital stock for the subsequent period. Accumulation of government debt builds the public debt stock that is served at a fixed interest rate both to domestic and foreign households. The public debt stock is split between domestic and foreign debt according to base year shares.

Emissions

The model's economic database is complemented with satellite databases on energy volumes (McDougall & Aguiar, 2008) and CO_2 energy-related emissions (Lee, 2008). Both energy volumes and emissions have an endogenous dynamic in the models and evolve the former, according to energy sector production, and the latter, proportionally to energy combustion processes and sectoral and household use of energy commodities.

Notes on scenario implementation

NDC targets were applied only to energy-related CO2 emissions.

CP and *NDC* scenario extensions assuming the same 2020-2030 emissions intensity change were achieved directly targeting emissions intensity and endogenously deriving the carbon price (which is consistent with the required abatement, but also with the policy cost in terms of GDP).

7. E3ME 6.1

Summary

The Energy-Environment-Economy Macro-Econometric model is a computer-based model of the world's economic and energy systems and the environment (Barker, 1998). It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessments, forecasting and research purposes. E3ME assesses the interactions between the economy, energy, and the environment.

As a global model, based on the full structure of the economic national accounts, E3ME can produce a broad range of economic, energy, and environmental indicators for the entire globe broken down into 61 regions, which comprise most major economies (including China, India, Russia, Brazil, Japan, Canada, Mexico, Indonesia, and the United States of America), the EU, at the regional level as well as at the national level (Member States plus candidate countries), and other countries' economies separately or regionally grouped.

Recent use cases include (Mercure et al., 2018), (Bachner et al., 2020), and (Wood et al., 2020).

Economic rationale

Economic activity undertaken by persons, households, firms and other groups in society has effects on other groups after a time lag, and the effects persist into future generations, although many of the effects soon become so small as to be negligible. But there are many actors and the effects, both beneficial and damaging, accumulate in economic and physical stocks. The effects are transmitted through the environment (with externalities such as GHGs), through the economy and the price and money system (via the markets for labour and commodities), and through the global transport and information networks. The markets transmit effects in three main ways: through the level of activity creating demand for inputs of materials, fuels and labour; through wages and prices affecting incomes; and through incomes leading in turn to further demands for goods and services. These interdependencies suggest that an E3 model should be comprehensive and include many linkages between different parts of the economic and energy systems.

Contrary to a typical CGE framework, where optimal behaviour is assumed and output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used, in E3ME the determination of output comes from a post-Keynesian framework and it is possible to have spare capacity. The model is more demand-driven and it is not assumed that prices always adjust to market clearing levels. The differences have important practical implications, as they mean that in E3ME regulation and other policy may lead to increases in output if they are able to draw upon spare economic capacity. The econometric specification of E3ME gives the model a strong empirical grounding. E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend. The dynamic specification is important when considering short- and medium-term analysis (e.g. up to 2030) and rebound effects, which are included as standard in the model's results.

Emissions

E3ME covers fourteen types of air-borne emission (where data are available), including the six GHGs monitored under the Kyoto protocol. This in essence includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and F-gases; land-use CO_2 (exogenously); and particulate matter (BC, OC, $PM_{2.5}$), sulphur oxides (SO_x), other nitrogen oxides (NO_x), and organic compounds.

Notes on scenario implementation

CP scenario:

Extrapolation of carbon prices was carried out from 2030 to 2050, in line with real GDP per capita growth from the recalibrated E3ME baseline; differences between extrapolated carbon prices and the E3ME carbon price assumptions were added on top of the recalibrated E3ME baseline from 2030 onwards.

Extrapolation of emissions intensity rate was implemented with average carbon intensity, based on GDP and CO_2 emissions from the E3ME baseline, reapplied to GDP projections to give implied emission targets for each region by 2050; differences between these emission targets and the E3ME baseline emission levels projected for 2050 were reconciled by adjusting a number of regional assumptions from 2030 onwards (capacity for different generation technologies, uptake rate of generation technologies, and of vehicle types).

NDC scenario:

Where additional policies (over and above current policies) were assumed in the IEA Stated Policies scenario, those assumptions were added on top of the current policies assumptions. Such policies include generation capacity constraints, technology mix for power generation, heating and road transport, fossil fuel regulations, restrictions or ambitions for reducing fossil fuel trade, increases in carbon prices and/or implementation of a carbon price in new sectors. Where no additional policies were identified from the IEA Stated Policies scenario and a region was expected to miss its NDC target by 2030 under the *CP* scenario by a significant margin, additional measures were implemented sequentially in the following order until the region was close to its NDC target: i) faster take-up of renewables for power generation and electric vehicles for road transport, ii) increased investment in energy efficiency improvements, and iii) higher carbon prices.

The two variants of the *NDC* scenario were modelled in a similar way to the Current Policies variants, with the addition of energy efficiency as one of the adjustments in the second variant.

All scenarios include the same treatment for recycling carbon revenues, which generates rebound effects in the economy. It was assumed that revenues from the carbon prices would be used by governments to partly fund energy efficiency investments. If carbon revenues were insufficient, governments would raise additional funds by increasing taxes for industries and households (with the burden being split equally between the two groups).

Supplementary Text 4: Harmonisation of socio- and techno-economic parameters

Supplementary Table 2 provides an overview of what parameters were harmonised by what models. By harmonisation, we refer to the process of aligning the inputs of the different models for producing the model inter-comparison study so as to reduce model response heterogeneity to the differences behind each model structure and theory (Schwanitz, 2013). This is not to be confused with model calibration, which refers to the determination of system parameters and behaviour based on external evidence rather than econometric estimation, as is typically done in IAMs (Nordhaus, 2017). In that sense, regarding historical data on which model behaviour is developed to align to observed trajectories (e.g., emissions), harmonisation requires that model-specific calibration databases be updated to shared historical databases. Similarly, regarding future assumptions to be used as inputs necessary for producing model outputs (e.g., socio-economic and techno-economic variables), harmonisation requires that shared assumption databases be used across the models. Here, we used the methodology documented in Giarola et al. (2021). We also note that, due to model-specific challenges, we achieved different levels of harmonisation. This means that, as highlighted in Supplementary Table 2, models were (a) harmonised explicitly to, (b) checked for consistency with, or (c) not harmonised to, the shared input databases outlined in Supplementary Tables 3-4. Checking for consistency for a particular model and type of variable means that, although harmonisation was not feasible/carried out, divergence of the model's input database values for this specific variable was reviewed and ensured to lie within a ±10% range of tolerance around the values of the shared database to which other models were harmonised.

In particular, we focused on the harmonisation of the following dimensions:

The *socio-economic development harmonisation*, which was made at the country level, consisted in a rigorous update of the SSP2 (Fricko et al., 2017) dataset, making adjustments to reflect more up-to-date sources for the European Union as well as to account for historical deviations between the SSP2 projections and historical data. The data sources were varied between short- & mid-term to long-term projections by country, ensuring smooth transitions in the projections. Supplementary Table 3 summarises the variables and data sources as harmonised across all the models.

The *techno-economic parameter harmonisation* was carried out performing an update of costs, fuel efficiency, and lifetime parameters for key low-carbon technologies in power, transport, buildings, and industry. The variables and technologies harmonised are reported in Supplementary Table 4. All the models except for ICES and FortyTwo applied consistently either a full techno-economic harmonisation or a consistency check across all the sectors covered exogenously due to their top-down nature. GEMINI-E3 could only perform harmonisation of the power sector, which is represented with higher granularity than other sectors in the model.

The level of *emissions harmonisation* varied across models and gas. All models' base years (2010 or 2015) have been compared to (i.e., checked for consistency with) a global, country-level disaggregated dataset for historical emissions of CO_2 and CH_4, the Community Emissions Data System (CEDS) for Historical Emissions (Hoesly et al., 2018) . The dataset was used to ensure that the models were aligned to the latest available CEDS data (2017 version) for the energy systems emissions, rather than a sector-level calibration. Specifically, all models used the same dataset for the calibration against the historical CO_2 projections. To the extent of representing these two types of emissions, all models except for MUSE were calibrated against the CEDS historical CH_4 emissions and other pollutants. Similarly, F-gases and N_2O were calibrated respectively against the NOAA dataset (World Meteorological Organization (WMO), 2018) and the PRIMAP dataset (Gütschow et al., 2016) in GCAM, GEMINI-E3, and E3ME. PM10 emissions were calibrated against the historical CEDS databases in GCAM, and E3ME.

Fossil fuel price harmonisation in computable equilibrium models (GEMINI-E3 and ICES) and macroeconometric models (E3ME) was based on the International Energy Agency World Energy Outlook (IEA, 2019). Calibrating resources input and supply curves to match fossil fuel price trajectory is the most common approach for fossil fuel resources, making it possible to control the key variable of fossil fuel prices taken from external energy scenarios. The benchmark fossil fuel prices from 2010-2018 used annual WEO data, deflated to reflect 2018 USD values. A linear interpolation was then applied to reach the WEO fossil fuel price trajectory of the years 2030 and 2040, ensuring consistency of the input data with a standard trajectory, by holding those critical years for the global climate target. Post-2040 fossil fuel prices were extrapolated using the same rate as 2030-2040. For more information, see Giarola et al. (2021).

Sectoral value added for E3ME was aligned against the EUROSTAT database (European Commission, 2020).

Interest rates and exchange rates for E3ME were aligned with the OECD database as common and consistent database (OECD, 2018) .

Supplementary Text 5: Comparison of temperature estimates

The temperature outcomes in this study are considerably lower than ranges estimated by Rogelj et al. (2016) (3.1-3.4°C for current policies; 2.6-3.1°C for unconditional INDCs; or 2.2-3.8°C when including scenario projection uncertainty) and the UNEP emissions gap report (United Nations Environment Programme, 2020) (3.4-3.9°C for current policies scenario and 3.0-3.5°C for unconditional NDCs, both with a 66% probability as 50% probability results not published). The temperature estimates in both Rogelj et al.(Rogelj et al., 2016) and the UNEP emissions gap report(United Nations Environment Programme, 2020) are based on using the IPCC AR5 scenario database to infer end-of-century temperatures from emissions levels in 2030 assuming current policies and NDCs. This method is very different from the method used in this study to estimate temperature outcomes. Among other things, it relies on a database consisting primarily of backcasting scenarios, which generally assume cost-optimal implementation of climate targets. The forward projections of mitigation efforts post 2030 based on near-term mitigation efforts used in this study to infer temperature outcomes avoids the reliance on backcasting scenarios, which are not designed to project where emissions are headed, but to analyse cost-effective pathways towards given targets. While one benefit of using IPCC scenario ensembles to infer temperature outcomes is a very high number of scenarios and models, a benefit of our approach is the use of projections which more closely match the logic associated with inferring future outcomes based on current actions, and the explicit nature of the modelling. The forward projections of emissions that lie behind the temperature estimates arrived at in this study have the important benefit of exposing what modelling choices and assumptions matter the most for future outcomes.

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