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Challenges in the harmonisation of global integrated assessment models: A comprehensive methodology to reduce model response heterogeneity

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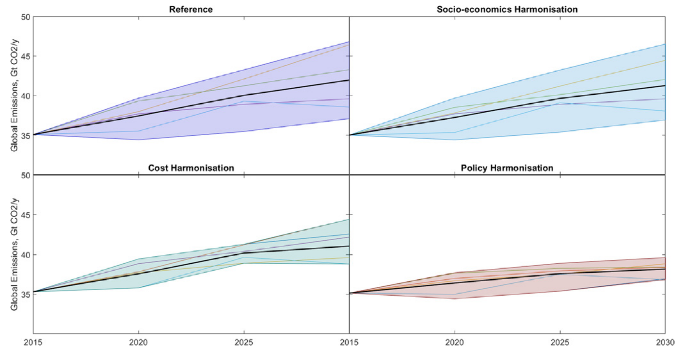
HIGHLIGHTS

- Step-by-step harmonisation on socio-economics, techno-economics, and policies
- Up-to-date open source data are supplied for socio-economics and techno-economics.
- The proposed harmonisation procedure reduces emissions gap to 2.3 Gt of CO2 in 2030.

GRAPHICAL ABSTRACT



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ABSTRACT

Harmonisation sets the ground to a solid inter-comparison of integrated assessment models. A clear and transparent harmonisation process promotes a consistent interpretation of the modelling outcomes divergences and, reducing the model variance, is instrumental to the use of integrated assessment models to support policy decision-making. Despite its crucial role for climate economic policies, the definition of a comprehensive harmonisation methodology for integrated assessment modelling remains an open challenge for the scientific community.

This paper proposes a framework for a harmonisation methodology with the definition of indispensable steps and recommendations to overcome stumbling blocks in order to reduce the variance of the outcomes which depends on controllable modelling assumptions. The harmonisation approach of the PARIS REINFORCE project is presented here to layout such a framework. A decomposition analysis of the harmonisation process is shown

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Model inter-comparison
Harmonisation

through 6 integrated assessment models (GCAM, ICES-XPS, MUSE, E3ME, GEMINI-E3, and TIAM). Results prove the potentials of the proposed framework to reduce the model variance and present a powerful diagnostic tool to feedback on the quality of the harmonisation itself.

1. Introduction

Climate change mitigation calls for a collective initiative of the scientific community to provide robust evidence of the consequences of climate actions (IPCC, 2018), and serve scientific research as well as policy design. Integrated Assessment Models (IAMs) have demonstrated their considerable potential to support the development of climate policies. Scenarios are key for characterising the complex interactions between humans and the environment in the long-term: they embed potential realisations of the future under pre-defined assumptions, they show how targets can be achieved, and may also describe how certain consequences can be avoided (O'Neill et al., 2020). However, crucial shortcomings are yet to be solved due to a lack of transparency of the modelling assumptions (Doukas et al., 2018), large variance across the modelling outputs (Fuss et al., 2014), and a limited inclusion of stakeholders in the scenario process (Doukas and Nikas, 2020). To address these issues, structured platforms of IAM modelling teams have been formulated, to stimulate model inter-comparisons, communicate to a non-expert community the IAM scenario storylines, and explain the implications of the results. These platforms include the initiatives of the Stanford Energy Modeling Forum (EMF) and of the Integrated Assessment Modeling Consortium (IAMC). Other national initiatives have been inspired by the same principles of increased transparency and legitimacy in the use of IAMs for climate policy design, including the Chinese Energy Modeling Forum (CEMF), hosted by Tsinghua University. In addition, the European Commission, through its Horizon 2020 programme, invited proposals to set up a European Energy Modelling Forum (Nikas et al., 2021).

At the heart of many model inter-comparison methods lies the harmonisation process, which is a methodology designed to align the inputs of different models for producing model inter-comparison integrated studies in which future climate outcomes, societal conditions, and policy assumptions are combined (O'Neill et al., 2020). Given the variety of the models and the diversity of the model inter-comparison study objectives, many different harmonisation protocols can be followed. Usually, the harmonisation exclusively focuses on aligning the scenario “narrative” within each model, as represented by assumptions governing the socio-economic developments underpinning future emissions pathways. The socio-economic development affects so heavily the energy systems dynamics, that studies aiming to explore the uncertainty of energy futures tend to compare contrasting narratives (Lugovoy et al., 2018). The IAMC has built five specific storylines, commonly known as the Shared Socio-economic Pathways (SSPS) (O'Neill et al., 2020). The SSPs include demographics, human development (for example, health and education), economic growth, inequality, governance, technological change, and policy orientations (O'Neill et al., 2014). They cover a range of qualitative factors (narratives that sketch broad patterns of change) and quantitative factors (population (KC and Lutz, 2017), Gross Domestic Product (GDP) (Dellink et al., 2017) (Crespo Cuaresma, 2017) (Leimbach et al., 2017), urbanization (Jiang and O'Neill, 2017), and educational attainment (KC and Lutz, 2017)). Each storyline is associated to a different future, ranging from a world with more sustainable behaviours (SSP1), lowering the challenge of both mitigation and adaptation, to a world with fossil fuel intensive growth and little regard for sustainability, creating significant challenges for both mitigation and adaptation (SSP3). An intermediate narrative is offered by the SSP2, known as the “middle of the road” storyline, which aims to project a socio-economic development reflecting business as usual trends. The choice of the storyline has a dramatic impact on the IAM outcomes. Some authors who have focused on the differences in the energy systems triggered by the specific narrative modelled with the GDP and population trends, Edelenbosch et al. (2020) projected carbon dioxide emissions of the three largest energy demand sectors (buildings, industry and transport) using a cross-demand sector model comparison (using GCAM, IMAGE, AIM/CGE and MESSAGE-GLOBIOM) against the different projected world socio-economics. They found that results led to a significantly large range: SSP3 showed highest increase in industrial emissions, whereas SSP2 had the highest increase in transport emissions.

Besides socio-economic development metrics, techno-economic assumptions constitute another critical part of IAMs. The techno-economic parametrisation proves to be crucial especially when technology-rich bottom-up models are used to generate the energy pathways to low-carbon futures. In their work, Krey et al. (2019) harmonised capital costs, operation and maintenance costs, conversion efficiencies, and lifetime for electricity generation technologies in the IAMs involved in the model inter-comparison study. They found that, despite the techno-economic mapping of the numerical values, variance can still be observed in the modelling output due the model structure (i.e. top-down versus bottom-up), their sector and technology granularity, as well as the energy systems response: in fact, although similar levelised costs of electricity would be obtained across models, each model would produce a different uptake of electricity. Additional difficulties of model inter-comparison studies, would come from the limited disclosure of techno-economic parameters and, when open databases are available, they are characterised by limited technology coverage (Shiraki and Sugiyama, 2020) (Krey et al., 2019).

Finally, shared climate policy assumptions (SPA) in the scenario definition within the harmonisation process, are key to link SSPs to the corresponding emissions; they are set to capture key policy goals, instruments and obstacles of mitigation and adaptation measures (Kriegler et al., 2014) (Kebede et al., 2018). Implementing policies in IAMs proves to be challenging. Among the barriers to policy harmonisation across models lies first of all the different technology and sector granularity across the models, which includes heterogeneous ways of resource extraction, power generation, fuel conversion, and end-use demand devices (Roelfsema et al., 2020). Until now, only a few exercises have been undertaken with a view to harmonising the representation of near-term policies. McCollum et al. (2018) applied an explicit modelling of near-term policies from a common database, the Climate Policy Database (NewClimate Institute, 2020) to estimate current levels of support in the G20 economies for energy efficiency and low-carbon energy investments in order to be aligned with meeting their NDC (Nationally Determined Contribution) targets; they concluded that considerably more capital would have to be mobilised to close the investment gap for a 2 °C or 1.5 °C-consistent future. Roelfsema et al. (2020) assessed the global and country impact of national climate policies and represented a set ranging between 42 and 94% of the high-impact policies from the seven G20 economies from the Climate Policy Database, showing that they accounted for 50 to 100% of possible greenhouse gas reductions. In order to increase the policy modelling coverage, model interlinkages were created to supersede the lack of representation of selected variables in some models; for example land use related policies were modelled using land use change projections from other models projections or international databases (such as the one made available from the Food and Agriculture Organization of the United Nations, the FAO).

Above all, the success of model inter-comparison studies relies on a clear and transparent knowledge share of the model hypotheses, assumptions, and behaviour across the modellers. In the recent contributions of the EMF 34 on cross-border energy trades between Canada, Mexico, and USA, Huntington et al. (2020) identified the crucial importance of data collection, exchange, and transparency in the modelling assumptions, especially because the data quality and availability varies significantly across the three countries. Highlighting further needs for model transparency, model documentation comprehensiveness, and data open access, Bistline et al. (2020) called for novel platforms for improving the multi-disciplinary conversation related to energy transitions. Dellink et al. (2020) also recommend to better document modelling baseline scenarios and the key assumptions underlying the numerical projections by creating an on-line space that contains the main model features, and link that to an online inventory of recent baseline projections.

Whilst it is promising to see an increasing appreciation of the need to harmonise assumptions across IAMs around socio-economic, techno-economics, and policies, there is a gap in the literature around specifically how such harmonisation should be undertaken, as well as a demonstration of the implications (in terms of model outputs) of the quality of the harmonisation procedure. This paper aims to fill this gap. First, we present a step-by-step methodology to harmonise each input, highlighting the complexities arising from the model structure, granularity of sector, and technology representation. Second, we present a harmonisation process which for the first time compared to the existing literature reflects up-to-date sources of socio-economic narratives and techno-economic parametrisation as well as to account for historical deviations (specifically over the period 2010–2020) between projections and reality. Third, being inspired by the principles of IAM transparency and legitimacy in the design of climate economic policies, we make the data sources used for the socio-economic, techno-economic, and policy harmonisation available as supplementary material and through the open access I2AM PARIS platform, developed within the PARIS REINFORCE project. Aside from technical and non-expert-friendly documentation of the modelling capabilities, the I2AM PARIS platform (I2AM Paris Platform) (I2AM Paris Platform, P.R, 2021) aims to share and display data presenting our processes of model harmonisation and interlinkages, as well as provide access to, illustrate and explain our modelling results.

2. Material and methods

2.1. Scenario protocol

The study proposes a step-by-step harmonisation process performed in the PARIS REINFORCE project. Each step adds a layer to the harmonisation starting from the each modeller's own assumptions. Each step is designed as a stand-alone scenario and helps build a diagnostic on the harmonisation itself, as detailed in the following:

- reference scenario, including the model embedded assumptions for each modelling team (R);
- starting from the reference, a scenario is built in which socio-economic inputs are harmonised as outlined in Section 2.2 (SH);
- starting from scenario SH, a scenario is built in which technology costs are harmonised (CSH) including the techno-economic inputs following the procedure discussed in Section 2.4.
- starting from scenario CSH, a scenario (PCSH) is built in which each modelling team implements a subset of the high impact policies reported in the policy database available as Supporting Material as feasible according to the model structure and as explained in Section 2.6

The simulations include a set of global bottom-up technology-rich models (GCAM (Edmonds et al., 1994), MUSE (Giarola et al., 2021), and TIAM (Loulou et al., 2005)) and computable general equilibrium models (GEMINI-E3 (Bernard and Vielle, 2008), ICES-XPS (Eboli et al., 2010)), and macroeconometric models (E3M3 (Barker, 1998)). In the following, we describe how socio-economics, techno-economics, policies, and other financial aspects were harmonised. The methodology includes references to the model 42, as, being part of the suite of global models in the PARIS REINFORCE project, its modelling structure affected procedural decisions taken during the harmonisation process. A summary description of the models is reported in Appendix A.

2.2. Socio-economic development

The socio-economic development is represented with demographic variables, such as population, urbanization, household size, population age, and education level, and macroeconomic variables, such as GDP, employment, real household income, sectoral value added, interest rates, and exchange rates. Among those, the parameters mainly affecting the energy demand and more widely described across all the models, were chosen for the harmonisation: population, GDP, interest rates, and exchange rates. As the latter two factors are financial aspects which highly depend on the former two, the methodology highly focuses on how GDP and population were determined.

2.2.1. Background

Despite the crucial importance of using a consistent trend in the socio-economic pathways to drive the energy demand, global GDP projections that range up to 2100 are scarce and, when available, very uncertain. The only existing source known for global data, the SSP database, which has been developed to feed IAMs (Dellink et al., 2017; KC and Lutz, 2017), has not been updated over time, and projections in the 2010–2020 period diverge from actually observed trends. For selected regions, such as the European Union (EU), the divergence from SSP2 could be relevant for both population and GDP growth, as shown in Table B.6.

Alternative methods relying on national government agencies figures of each country are not recommended. In fact, although they would be free of discrepancies compared to national or regional projections, international effects are generally underestimated.

2.2.2. Approach

In the PARIS REINFORCE project, we built a GDP and population database to account for the most up-to-date sources of socio-economic narratives. Examples of source trajectories and final trajectories used in the study for the population growth and GDP growth in the USA, Turkey, and Australia are presented as examples in Fig. 1 and Fig. 2. To create a consistent dataset between population and GDP, it is key to link GDP growth with the size of the working age population which needs being converted into labour force (or active population) (Fouré et al., 2020).

We have followed a set of priorities to which the socio-economic trajectory has to fulfil. The assumed trajectories for GDP and population should be up-to-date; they should come from a reliable source; they should present consistency between (working age) population and GDP growth rates, defined following a specific path (e.g. based on fertility and mortality for population, and business cycles for GDP); and they should be characterised by a consistent geographical granularity. Maximising these conditions, we have used three different approaches for the following sets of countries:

- European Union, United Kingdom, Norway, representing 8.2% of global population, 17.2% of global GDP. The following data sources were used: EUROPOP for population projections until 2100 (European Commission, 2020); Ageing Report for GDP per capita projections until 2070 (European Commission, 2017); SSP2 Env-Growth for GDP per capita projections after 2070 (Dellink et al., 2017).
- Rest of the countries in the OECD database (rest of OECD, Argentina, Brazil, China, Colombia, Costa Rica, India, Indonesia, Saudi Arabia, and South Africa), representing 57.8% of global population and 62.8% of global GDP. The following data sources were used: OECD statistics for short-to-medium term population projections (OECD, 2020); OECD Economic Outlook n. 106 for GDP growth until 2021 (OECD, 2018); OECD Economic Outlook n. 103 for GDP growth on medium-

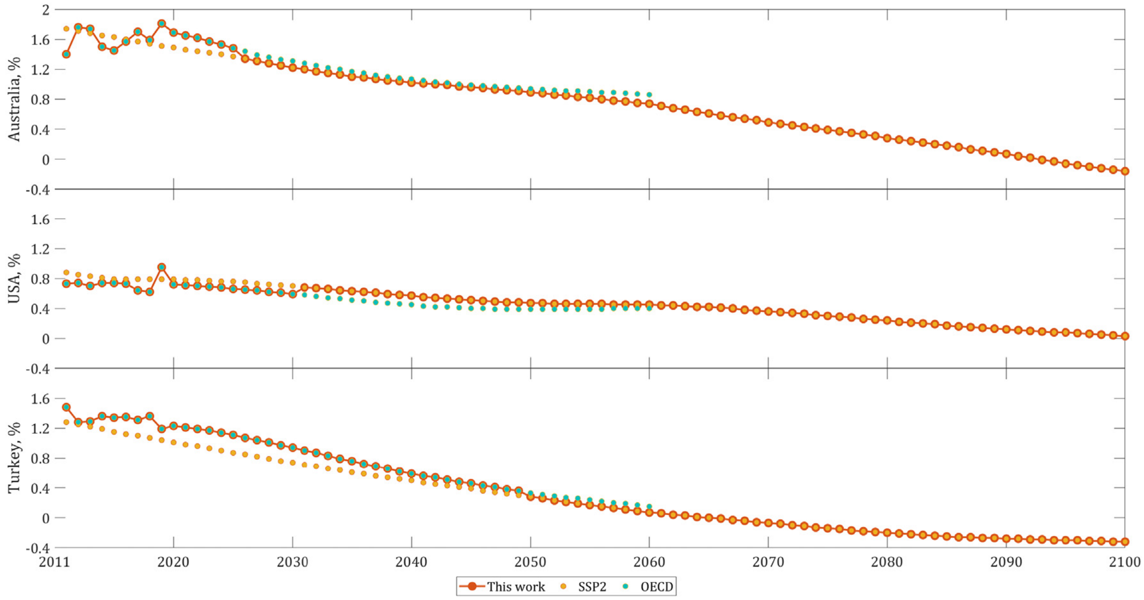

Fig. 1. Population growth (%) trajectory comparison between the different sources, such as SSP2 (KC and Lutz, 2017), OECD (OECD, 2020), and the final trajectory chosen in this study, for Australia, USA, Turkey.

term (beyond 2021) (OECD, 2019); SSP2 IIASA for long-term population projections (KC and Lutz, 2017); SSP2 Env-Growth for long term GDP growth projections (Dellink et al., 2017). The year at which the switch was made (from “short-to-medium” to “long” term) varies by country aiming to produce a smooth transition between the projections (as reported in Table B.11). Selected examples of the constructed projections are reported in Table B.12 and B.13;

- Other countries, representing +/— 34% of global population, +/— 20% of global GDP by 2010. United Nations database for population estimates until 2020 (United Nations, 2019); International Monetary Fund World Economic Outlook database for GDP growth estimates until 2020 (International Monetary Fund, 2019); SSP2 IIASA for post-2020 population projections (KC and Lutz, 2017); SSP2 Env-Growth for post-2020 GDP growth projections (Dellink et al., 2017);

Among the remaining socio-economic input data, interest and exchange rate also affect greatly the modelling for specifying the current account and fiscal balances. Interlink-ability between regions through interest and exchange define the transmission and direction of capital flows which is further determined by productivity growth (Bekkers et al., 2020). Consistent with the approach used for GDP and population, the exchange rate (USD /National Currency) and both short- and long-term interest rates (percent) were chosen to follow the historical data and projection of the 2018 OECD Economic Outlook (OECD, 2018); they were integrated for some missing EU member states, with the EUROSTAT database (European Commission, 2020). Both interest and exchange rates were assumed to be constant after the year 2060. The overview of the harmonised socio-economic variables is presented in Table 1.

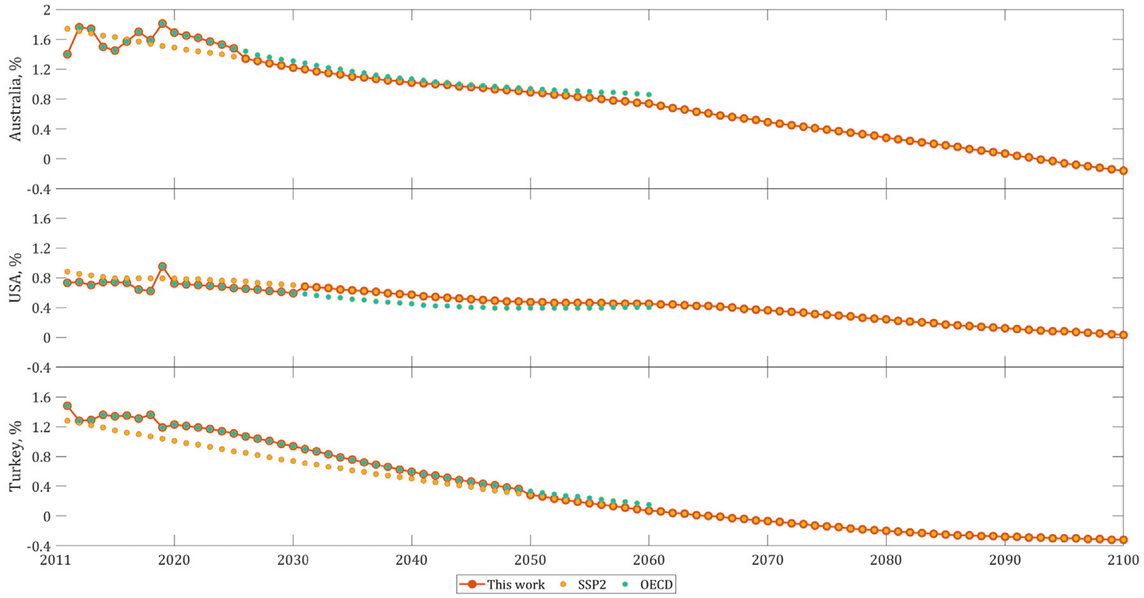

Fig. 2. GDP growth (%) trajectory comparison between the different sources, such as SSP2 (Dellink et al., 2017), OECD, (OECD, 2018) until 2021 and (OECD, 2019) beyond 2021, and the final trajectory chosen in this study, for Australia, USA, Turkey.

Table 1
Socio-economic variable harmonisation: (v) consistency check, v full harmonisation, o model output, x not represented, blank not harmonised input. GEM: GEMINI-E3.

Model	GCAM	TIAM	model 42	MUSE	ICES-XPS	GEM.	E3ME
Population	v	v	v	v	v	v	v
GDP	v	v	v	v	v	v	v
Interest rate	x	x	o	x	x	o	v
Exchange rate	x	x	o	x	x	o	v

Table 2
Historical emission inventory harmonisation: (v) consistency check, v full harmonisation, o model output, x not represented, blank not harmonised input. GEM: GEMINI-E.

Model	E3ME	GCAM	GEM.	ICES-XPS	MUSE	TIAM	Model 42
CO_2 emissions	(v)	(v)	(v)	(v)	(v)	(v)	(v)
CH_4 emissions	(v)	v	v	v			x
N_2O emissions	(v)	v	v	v			x
F-gases	(v)	v	v	v	x	x	x
Other pollutants	(v)	v	x	x	x	x	x

2.2.3. Implementation

All the models performed a full harmonisation and aligned their socio-economic drivers of the energy demand (population and GDP) to the harmonised database (which can be downloaded as Supporting Material). The implementation method, though, might differ across models. For example, bottom-up models (such as TIAM, MUSE, model 42, and GCAM), use the socio-economic drivers as pure exogenous input trajectory which enters energy service correlations, whereas in top-down models (such as ICES-XPS, GEMINI-E3, and E3ME) the parameters would be linked to additional macro-economic variables.

Interest rates and exchange rates are important variables to characterise the financial sector, typically well represented only in macro-economic models. In the model suite, interest rates and exchange rates are used as model inputs by E3ME exclusively, which therefore aligned their inputs to the given harmonised trajectory.

2.3. Historical emissions

2.3.1. Background

Modelled emissions need to be aligned across models. Current approaches identify a model benchmark year, normally the last calibrated year, to estimate deviations from historical emission inventories. To reduce short-term variance up to 2030, alignment with historical emissions should remain within a 10% of deviation from the inventories of the total greenhouse gas emissions (Roelfsema et al., 2020).

2.3.2. Approach

The global models were aligned to the same and the most up-to-date emissions databases, having global coverage and country-level disaggregation. Historical inventories of CO_2, CH_4, and pollutants were based on the Community Emissions Data System (CEDS) for Historical Emissions (Hoesly et al., 2018); F-gases were aligned against the NOAA dataset (Chemical Sciences Society, 2018); N_2O were aligned against the PRIMAP dataset (Gütschow et al., 2019).

2.3.3. Implementation

A key challenge in the historical emissions alignment process, was represented by overcoming the differences between the benchmark databases and the model-specific calibration database.

Many model use the International Energy Agency database for the model calibration. Typically economic activities and their emissions undergo classification which are specific to each database, leading to sectoral differences which are hard to reconcile. In order to overcome the sectoral deviations, still maintaining the alignment to the selected databases, we opted for matching the emissions of the national energy system of each country as a whole rather than going down the path of a sector-by-sector mapping. Database mapping is a field of active and growing research which could be properly assessed in purposed-designed model intercomparison projects (Andrew, 2020).

Table 2 maps the emissions harmonisation as performed in each model.

The focus of the harmonisation was primarily on CO_2 sources across all models. The models where land use change was explicitly accounted for, such as GCAM, GEMINI-E3, and ICES-XPS also performed a full harmonisation of pollutants different from CO_2.

2.4. Techno-economic harmonisation

2.4.1. Background

Techno-economic parametrisation is key source of variations across models; assumptions on costs could be more influential on the model output than model behavioural uncertainties (Bosetti et al., 2016). Harmonising techno-economics inputs has proven to be complex due to inter-model technology mapping and inter-model parameter mapping (Krey et al., 2019).

2.4.2. Approach

The techno-economic assumptions for power, transport, industry, residential and commercial sectors were harmonised across all models, according to these steps:

- selection of representative technologies with the wider description shared across the models
- critical comparison of base year and projected costs (capital and operating and maintenance), efficiencies, and lifetime from the internal TIAM database against up-to-date databases; specifically the European NECP reports were used, based on Mantzos et al. (2017).
- regional cost modelling using regional cost factors reflecting labour costs

The power sector technologies whose parameters were shared across the models were: onshore wind, offshore wind, solar photovoltaics (utility and rooftop), concentrated solar power, pulverised coal, oxyfuel coal, coal integrated gasification combined cycle, natural gas combined cycle, natural gas combined cycle oxyfuel, geothermal, nuclear, biomass combustion, and electricity storage.

The transport sector technologies whose parameters were shared across the models identified the key transport modes to target for the decarbonisation of the sector, such as buses, cars, light trucks, medium trucks, commercial trucks, and heavy trucks. Each transport mode was characterised using conventional fuels (either petrol, diesel, LPG, or natural gas), biofuels (either ethanol, methanol, or hydrogen), or electricity (battery or hybrid vehicles). As a general assumption to move from a cost per vehicle to vehicle-km, an average travelled distance in Europe equal to 13,000 (light), 37,000 (medium), and 52,000 (heavy) km per year was assumed respectively for each class of truck.

In industry, the focus was on mitigation technologies such as carbon capture and storage (CCS) in cement and steel manufacturing. We first harmonised the assumption on capture rate, which is a key harmonisation parameter to determine the increase costs of capital and operational for a technology, as evident in power generation (van Vuuren et al., 2017). Then, we harmonised cost assumption, from available studies which have disclosed their techno-economic assumptions (Gardarsdottir et al., 2019) (Schorcht et al., 2013).

In the residential and commercial building sector, heating, cooling, and cooking display a wide fragmentation across the models. Benchmark values were defined calculating the additional costs due to the relative improvements of advanced technologies compared to the corresponding standard technology. This implied a process of cost normalisation over the efficiency. Only a high-level alignment of costs and performance was requested for this sector due to the significant uncertainty of the benchmark values and the large variability of the representation of the sector across the models.

A summary of the reference metrics and sources is presented in Table B.7 for the power sector, in Table B.8 for the transport sector, in Table B.9 for the industrial sector, and in Table B.10 for the building sector.

The shared techno-economic database for power, transport, and buildings is available as Supplementary Material to this paper.

2.4.3. Implementation

The techno-economic parameters harmonisation was carried out performing an update of costs, fuel efficiency, and lifetime parameters for key low-carbon technologies. A full parameter harmonisation is a direct substitution of the benchmark values after standardisation, when a direct correspondence between the internal and the benchmark technologies was established. A consistency check implied an analysis of the deviations between standards and advanced technologies parameters. Most models performed a full harmonisation in power and transport; a consistency check was dominant in the building sector, whereas only selected technologies (CCS) were targeted for the harmonisation process in industry. Within this, all the bottom-up models except model 42, applied consistently either a full parametric harmonisation or a consistency check. Computable General Equilibrium models (CGE) and macroeconometric models have a lower technology granularity or include endogenous treatment of technologies which is a barrier to a full harmonisation (see Figure B.6 and Fig. B.7). More specifically, in E3ME technology costs represent a model output. In ICES-XPS, where this harmonisation step was not feasible, because the technology cost computation is endogenous as the cost structure itself may vary within the simulation, the scenario was modelled applying harmonisation on fossil fuel prices. For GEMINI-E3, the cost harmonisation procedure was implemented in two steps: the first step was a consistency check that the technology costs used as reference for the base year were close to the benchmark (e.g., the nuclear generation cost in USD per kWh); the second step was the introduction of technical progress to replicate the expected evolution of the cost within the simulation period.

Table 3 represents the mapping of the techno-economic harmonisation across the models.

2.5. Harmonisation: other data inputs

2.5.1. Background

In addition to labour and capital, fossil fuels play a key role as macroeconomic drivers of baseline scenarios. Fossil fuels represent 80% of the world's total primary energy; thus, a reliable representation of its supply in the baseline scenario is critical to anchor the alternative energy and the low carbon transition (Fouré et al., 2020). Calibrating resources input and supply curves to match fossil fuel price trajectory is the most common approach for fossil fuel resources. This calibration approach makes possible to control the key variable of fossil fuel prices taken from external energy scenarios. It has several drawbacks, however. As fossil fuels demand depends heavily on economic activity, the selected fossil fuel prices may be inconsistent with the baseline fossil fuel demands, which could be quite different from the one used in the external energy scenario used (Chen et al., 2017).

2.5.2. Approach

There are two primary potential sources for fossil fuel prices that include the World Energy Outlook (International Energy Agency, 2019) and the International Energy Price Assumption from the European Commission. WEO 2019 current policy projection was chosen for fossil fuels price assumption for several reasons. First, its projection is based on the more recent historical value (2018). This ensures the consistency and trends of energy price given by European Commissions in the energy and climate plan. Second, the WEO price trajectory seems more realistic to reflect implemented climate policies by the higher price assumed for imported fossils such as coal. The benchmark fossil fuel prices from 2010 to 2018 used annual WEO data, deflated to reflect 2018 Dollar value. A linear interpolation was then applied to reach the WEO fossil fuel price trajectory of the year 2030 and 2040. This ensures the consistency of the input data with a standard trajectory, holding those critical years for the global climate target. Post-2040 fossil fuel prices were extrapolated using the same rate as 2030–2040.

Table 3

Techno-economic harmonisation: (v) consistency check, v full harmonisation, o model output, x not represented, blank not harmonised input. GEM: GEMINI-E.

Model	E3ME	GCAM	GEM.	ICES-XPS	MUSE	TIAM	Model 42
power	o	v	v		v	v	
storage	x	v			v		
road transport	o	v	(v)		v	v	
buildings		(v)			(v)	v	
industry CCS					v	v	

2.5.3. Implementation

Harmonisation of fossil fuel prices (namely gas, oil, and coal) was performed in the macroeconometric (E3ME) and CGE models (ICES-XPS, GEMINI-E3) used in the study. The remaining models are bottom-up and either determine fuel prices as an output or do not represent fuel prices as at all, thus making irrelevant a harmonisation according to this dimension. Table 4 summarises how the harmonisation was performed in each model in terms of fossil fuel prices.

2.6. Policies

2.6.1. Background

A shared database of current policies implemented globally, with a regional granularity, was developed, building on the Climate Policy Database (NewClimate Institute, 2020). Compared to the Climate Policy Database, we identified superseded policies, updated targets for extended policies beyond 2020, and new policies with a focus on key emitting countries and benefiting from feedback of national modelling groups in the PARIS REINFORCE project. Specifically, policies were updated for Russia, India, European Union, USA, Japan, Brazil, and China. The developed policy database is available as Supplementary Material, which presents the list of policies, of NDCs, as well as the detail of which policy has been implemented by each model and how. The comprehensiveness of the policies implemented had differing spatial extent over the world's regions, where some regions, like Europe and India, were more represented than others, as shown in Fig. B.16.

2.6.2. Approach

Policies were classified depending on coverage, which means whether they are applied on a system or a sector level (namely, industry, transport, power generation, buildings, land, and fossil supply). Additionally, policies were classified according to their type, which includes: cap on emissions (i.e. limit on emissions), cap on fossil fuel use (i.e. limit on fossil extraction), economic (i.e. carbon tax), quality of the energy access, clean energy targets (i.e. minimum levels of renewables or of electric vehicles), efficiency standards (i.e. standards on fuel efficiency or on emission intensity), and land use (i.e. destination of lands, such as afforestation). Overall energy access is under-represented, as only 1 policy is present in the database.

The policy implementation in a model implies to perform decisions on.

- Start year. This represents the milestone year closest to the year when a policy is enforced. If not available, the first available year after the calibration was chosen.

Table 4

Fossil fuel price projections: (v) consistency check, v full harmonisation, o model output, x not represented, blank not harmonised input. GEM: GEMINI-E.

Model	E3ME	GCAM	GEM.	ICES-XPS	MUSE	TIAM	Model 42
Fossil fuel prices	v	o	v	v	o	o	

- End date. This is the milestone year closest to the year when a policy stops. If unspecified, 2030 was assumed as the end year.
- Multiple year extension. For policies applied over multiple years between the start year and the end year an interpolation should apply, which is typically linear
- Target variable. Depending on the sector and type, a specific model variable needs to be defined for an appropriate representation of the policy. For example, a share of renewables (or biofuels) in a region should target the variables representing the ratio of the renewable generation (or biofuel consumption in road transport) compared to the total generation from the power sector (total consumption of fuels in road transport). More details on the policy modelling are available in Appendix A whereas the Supplementary Material contains the implementation method for each policy.
- Reference variable. For policies which defined an absolute or percentage deviation in the value of a variable, a variable needs to be identified to represent the value of the selected variable in the year taken as reference for the policy implementation
- Regional aggregation. Policies can be defined for larger (smaller) territories compared to the modelled regions. In these circumstances, an aggregation rule should apply and a factor scaling up (down) the policy target is calculated using an appropriate reference variable. For example, a minimum emission reduction in Argentina should apply to a hypothetical Latin America region, multiplying the amount of the reduction targeted by the policy by the share of emissions from Argentina in Latin America in the reference year defined by the policy.

2.6.3. Implementation

Power and transport are the sectors recipient of the highest number of policies, as shown in Fig. B.8, Fig. B.9, and Fig. B.10, which also provide a breakdown of the policy implementation by sector-model.

3. Results and discussion

In the following, the results are presented for the reference scenario (R), the socio-economic harmonisation scenario (SH), the techno and socio-economic harmonisation scenario (CSH), and finally for the policy, techno- and socio-economic harmonisation scenario (PSCH) as obtained from the models: E3ME, GCAM, GEMINI-E3 (GEM.), ICES-XPS, MUSE, and TIAM.

The analysis is based on global simulations performed between the model base year and 2030. The variance across models is studied for key variables such as global emissions, final energy, and power generation in 2030. 2030 was chosen for two reasons. First, 2030 is the end year for the majority of planned and implemented policies. Second, the year is sufficiently far from the last updated year after the calibration (2017) and it is represented across all models, despite their differences in the simulated time interval.

3.1. Emissions

Fig. 3 shows that effectively the each one of steps of the harmonisation leads to a reduction in emissions aligning the emission trajectories across the models and reducing the variance from a range of 37–47.3 Gt CO_2 down to 36.8–39 Gt CO_2 in 2030.

Despite being acknowledged as being among the main responsible for the model deviations (Roelfsema et al., 2020), the socio-economic harmonisation (SH scenario) in fact, produces more relevant effects in some models (GEMINI-E3 and MUSE) compared to others (like ICES-XPS). This can be explained as models with the smaller divergences use a socio-economic trajectory in their R scenario already close to the harmonised one (SH). Deviations between R and SH, due to socio-economic development harmonisation, in 2020 are less evident as this is close to the last updated year (see Fig. B.11 for the global emissions and Fig. B.12 for the global final energy).

Effects on emissions in scenario CSH are less relevant in CGE models compared to technology-rich models with a high technology granularity (see Fig. B.6 and Fig. B.7). Among the bottom-up models, GCAM shows the largest emission reductions due to the deviations of costs compared to the reference (R).

The policy implementation produces in each model a remarkable reduction in emissions. The highest reductions are in GEMINI-E3, GCAM, and MUSE. The reduction in emissions is not therefore just dependent on the number of policies implemented but is more linked to the implementation of highest-impact policies. These policies are those bringing the highest reduction in emissions and vary by model; they are summarised in Table 5 whereas they are marked in bold in the Supplementary Material. Interestingly, CGE models are stronger in setting up system-wide policies compared to technology-oriented policies. In fact, aside from the power sector, where renewable uptake can be modelled, policies in transport are not represented in these models. This has strong implications considering that transport is a sector with historically high growth in energy demand. Lower electrification levels in transport would also imply that

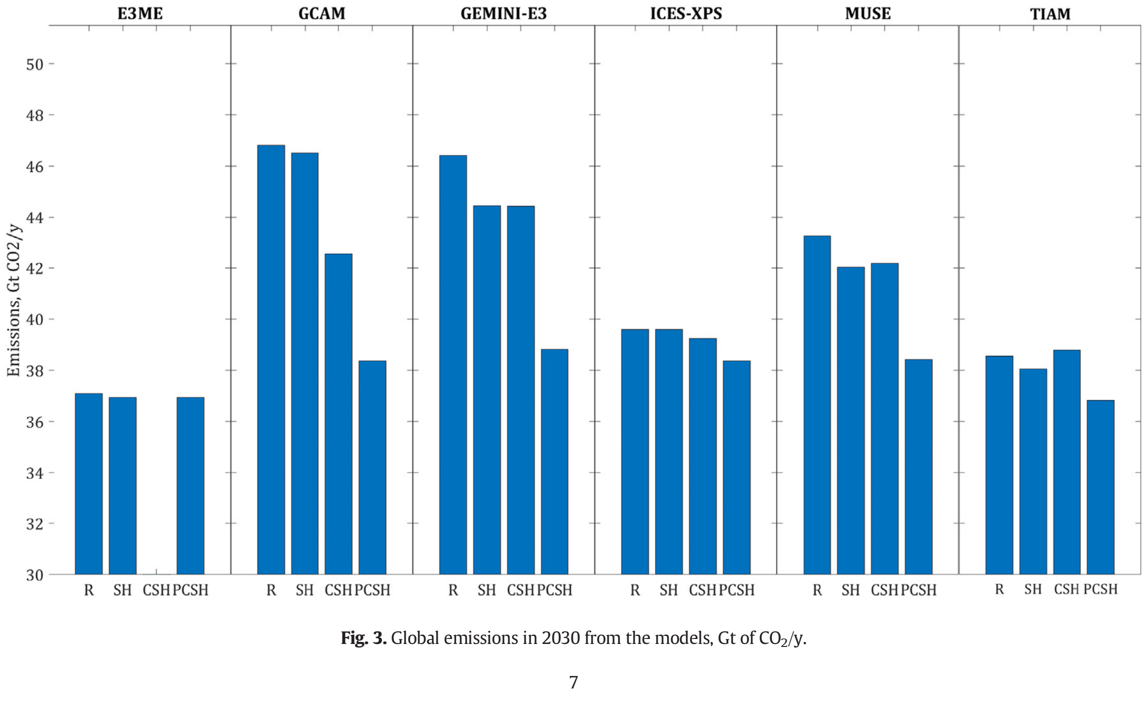

Fig. 3. Global emissions in 2030 from the models, Gt of CO_2/y.

Table 5
List of impact policies by model.

Policy type	Application remit
Economic	Energy System (example: carbn price)
Clean energy	Power, transport (example: renewable generation share targets)
Clean energy	Energy System (example: renewable consumption)
Target use	Land (example: afforestation targets)
Efficiency standard	Power, transport, buildings, industry (example: vehicle fuel efficiency targets)
Cap on emissions	Industry, buildings (example: limit on industrial emissions per unit of gross added value)
Cap on emissions	Energy System (example: energy systems emission cap)

policy synergies (between transport and electricity generation) would be less influential on driving emissions reduction.

The residual divergence in emissions across models are due to the limits on the techno-economic parametrisation, especially when it comes down to key parameters governing the diffusion of novel technologies (such as growth rates, capacity limit, and capacity addition limit), assumptions on elasticity of energy demand to the socio-economic drivers, and, above all model behaviour. In addition to the distinction between bottom-up and top-down CGEs (ICES-XPS and GEMINI-E3), model behaviour differs between those using a cost-minimisation approach (such as TIAM), those using a simulation approach (such as GCAM), and those using an agent-based approach (MUSE).

3.2. Energy supply and demand

In all the models, a decreasing trend in emissions is accompanied by a reduction in the final energy demand (see Fig. 4). The reduction in final energy has different magnitudes depending on the pace of the decarbonisation in the power sector due coal-to gas substitution and renewables (see Fig. B.15).

Transport is the sector which across all models sees the largest energy demand reduction when moving from the reference (R) to the policy scenario (PCSH) (see Figure 5). Macro-economic and CGE models show a constant or even higher energy demand. The opposite behaviour depends on the policy coverage for the transport sector: in this sense bottom-up models have the capacity, absent in CGE and macro-economic models, to model policies which target specific transport technologies.

Bottom-up models such as GCAM, MUSE, and TIAM present a reduction in liquids driven by policiees, specifically fuel efficiency targets. Solids have phased out or are to be phased out in all models; in MUSE some residual coal is still used in rail transport. Gases seem to not play a too relevant role and their share is bound to remain constant or reduce in all models. Models do not agree on the electrification uptake, which increases in GCAM and MUSE but reduces in TIAM. Further sensitivity analyses would be needed to understand the opposite trend. Typically, there could be system effects due to an increase in the electricity price, or there could be other constraints linked to growth rate, maximum capacity limit, or maximum capacity addition for specific technologies in transport.

In the CSH scenario, the harmonisation process was limited by difficulties with mapping the benchmark technologies in buildings and industry with the technologies represented in each model, due to the diverse technology suite used in each model. For this reason, in fact, bottom-up models such as GCAM, TIAM, and MUSE applied primarily consistency checks on the relative deviation of techno-economic indicators of low-carbon technologies (such as advanced lighting systems or steel manufacturing integrated with a CCS plant) compared to a standard technology (conventional lighting or conventional cement manufacturing).

In the building sector, results show a relatively stable final energy consumption across all models up to the CSH scenario (see Figure B.13). The implementation of policies (PCSH scenario), produces the highest final energy reduction in GCAM, whereas MUSE shows overall a slight increase in the demand driven by the increase in electrification. All the models agree showing a reduction in the use of solids and higher electrification rates.

In industry (see Figure B.14), stable emission trends are shown in MUSE and TIAM. A reduction in final energy, as shown by GCAM and ICES-XPS, is led by efficiency improvements, although GCAM also projects an increase in electrification. Policies implementing sector-wide emission reduction are among the drivers of these changes.

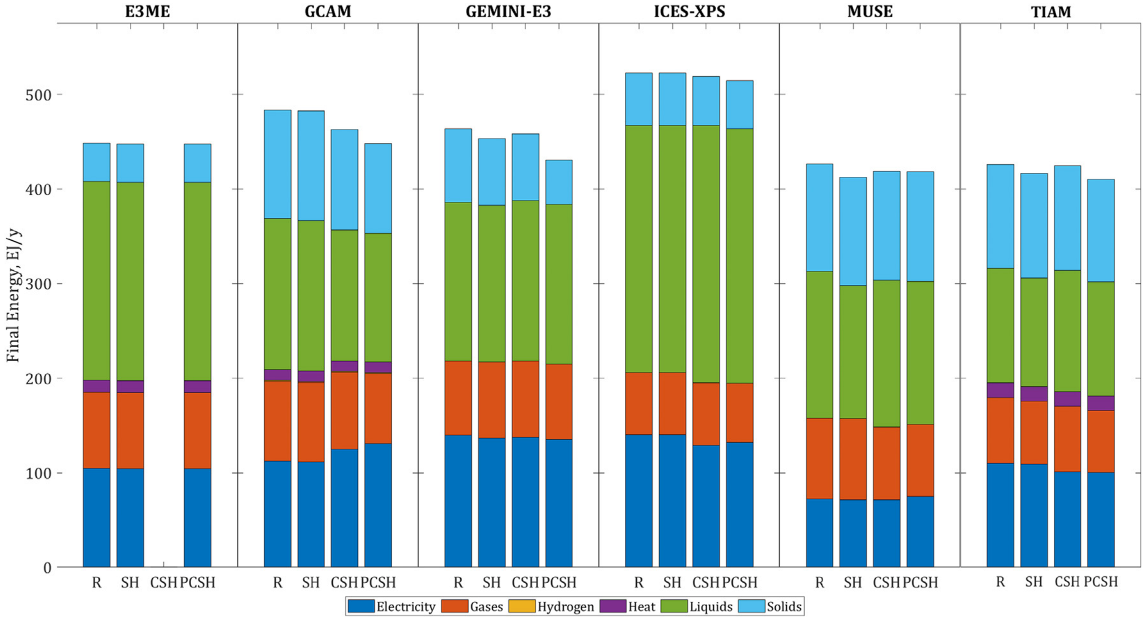

Fig. 4. Final energy in 2030 from the models, EJ/y. The chart reports the consumption in all the demand sectors of electricity, of gases (coming either from bioenergy, such as biogas and biomethane, or from fossil, such as natural gas), of hydrogen, of heat, of liquid fuels (obtained either from bioenergy, such as biofuels, or fossils, such as petrol or kerosene), and of solids (obtained either from biomass or fossils such as coal).

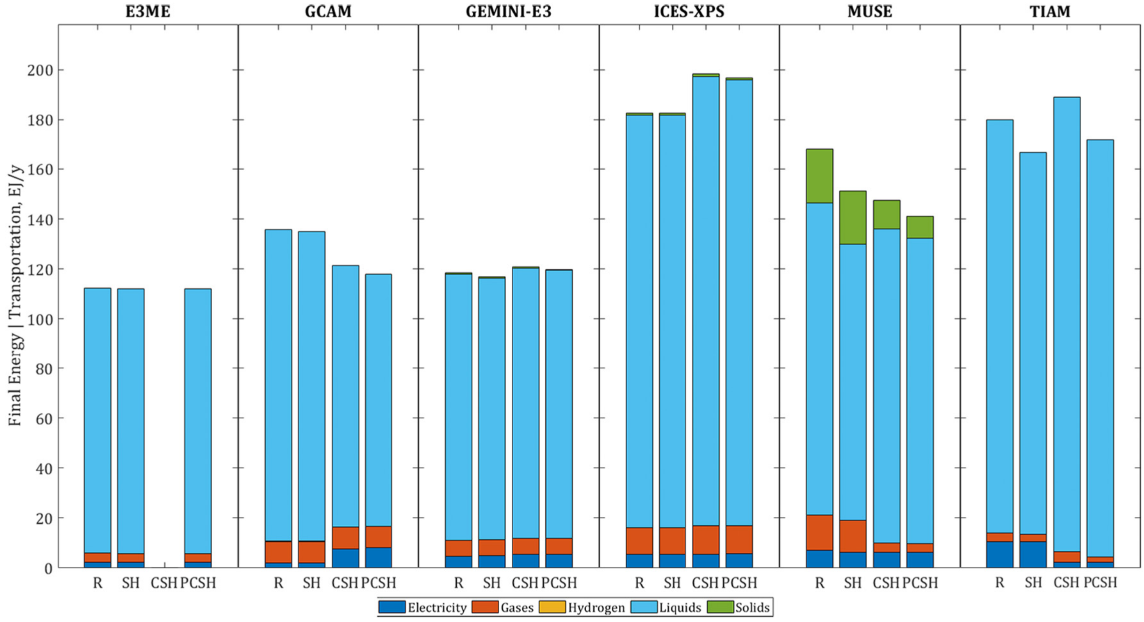

Fig. 5. Final energy in transport in 2030 from the models, EJ/y.

Models differ in terms of energy systems electrification as shown by the divergences in the power sector (Fig. B.15, where GCAM and ICES-XPS show the highest electricity generation. Notably, the divergences in electricity generation would come from a different level of electrification of industry and buildings. On the one side, these deviations could relate to lack of harmonised inputs such as the energy demand elasticity to the socio-economic drivers, as well as to weakly harmonised inputs such as costs in industry and buildings. On the other side, there are structural differences which explain why MUSE should present the lowest electrification levels in both sectors: the lack of industrial options running on electricity only and the inertia of the buildings agents to changes in fuel types.

4. Conclusions

A clear and transparent approach to integrated assessment modelling is key to deliver robust scenarios based on model intercomparison studies. This is the first scientific contribution focusing on displaying a step-by-step methodology for the integrated assessment modelling harmonisation. The methodology applies to bottom-up models, computable general equilibrium models, and macroeconomic models. It involves sequentially: harmonisation of key socio-economic drivers (gross domestic product, population, interest rate, and exchange rates); harmonisation of techno-economic assumptions (with a focus on key low-carbon technologies in power, buildings, industry, and transport) and other economic aspects related to fossil fuel prices; and harmonisation on climate-related policies implementation.

The harmonisation approach implemented allows to reduce inter-model variance of the CO_2 emissions in 2030 to below 2.3 Gt of CO_2, much lower than the most recent literature in the field (Roelfsema et al., 2020). The step-by-step harmonisation methodology here proposed, stressed the crucial importance of including policies in the harmonisation process, in addition to the established harmonisation of gross domestic product and population. In fact, the integration of current policies provides a more homogeneous ground for the development of energy futures where diffusion of renewables, fuel efficiency standards, and electrification levels constrain the autonomous model evolution and reduces the model divergence. The methodology highlighted the challenges of a full techno-economic harmonisation, as it can be performed more rigorously when the model structure presents similarities, and the benchmark parameters can be more easily mapped as model inputs. Responsible for the residual divergence across models are non-harmonised assumptions on the techno-economic parametrisation, the elasticity of energy demand to socio-economic drivers, and model diversity. Future work for the development of the proposed harmonisation procedure would involve standardisation of global discount rates, which, responsible for the intragenerational distribution of climate policy costs, might play a crucial role in some models when deep mitigation is concerned and a high renovation of the energy system is required. It needs to be stressed that, in addition to costs, technology capacity growth rates may have high impacts on the results. Additional areas of further development would be the standardisation of technology hurdle rates, which can be challenged by the diversity in the representation of technologies across models, being in some cases an exogenous input or being endogenously calculated in the model. Research in the area of harmonisation would also imply analysing the effects of service demand elasticities, where it becomes a crucial uncertainty to identify the response of the energy systems in terms of commodity (other than fuels) demand to changes in prices, policies, behaviours, and socio-economic development. It is fair to note that we are still far from an integrated approach that standardises all the possible data inputs across all the model types and adaptable to any model structure. However, using a step-by-step harmonisation such as the one presented in this work provides an effective diagnostic procedure on the quality of the harmonisation itself. At the same time, we acknowledge that the harmonisation should serve more as a tool to understand model results, favouring the result diagnostics, enriching results robustness, and providing ground to the explanations of model deviations, rather than a tool for flattening all the model differences.

Alongside the harmonisation methodology, this work contributes to providing a dataset of socio-economic development indicators especially updated in the short-term trajectories to account for historical trends until 2020 and to provide a more realistic basis for the projections until 2030. In addition, an open access technology database with updated global costs of existing and low-carbon technologies is provided for the power, transport, and building sectors. Finally, an updated policy database is presented with more than 20 high-impact policies added compared to the recent work by Roelfsema et al. (2020).

Symbols

Acronyms

ASDI	Aggregated Sustainable Development goal Index
BRICS	Brazil, Russia, India, Indonesia, China and South Africa
$B - vkm$	billion vehicle per km
CCS	Carbon Capture and Storage
CES	Constant Elasticity of Substitution
CEMF	Chinese Energy Modelling Forum
CGE	Computable General Equilibrium Model
GHG	Greenhouse Gases
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
LPG	Liquefied Petroleum Products
NDC	Nationally Determined Contributions
OECD	Organization for Economic Co-operation and Development
O & M	Operation and Maintenance
PPP	Purchasing Power Parity
PR	PARIS REINFORCE project
SPA	Shared climate Policy Assumptions
SDG	Sustainable Development Goals (SDG)
SSP	Shared Socio-Economic Pathways
UN	United Nations

CRediT authorship contribution statement

SG. coordinated the protocol for scenarios, which were designed by all authors, and M.V.; A.G., S.G., S.M., A.N., and D.-J.v.d.V. coordinated the harmonisation protocol; all authors were involved in the model analysis, with notable contributions from D.-J.v.d.V., J.M. (GCAM), A.G., A.Kob., N.G., S.M. (TIAM), S.G., A.H. (MUSE), S.P., M.V. (GEMINI-E3), L.C., E.D. (ICES), A.A.-K. and H.B. (E3ME). S.G. compiled and analysed the results, and created the figures, with feedback from all other authors. S.G. coordinated the conception and writing of the paper; all authors provided feedback and contributed to writing the paper.

Declaration of competing interest

We have no conflicts of interest to disclose.

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Appendix A. Model overview

GCAM 5.3. 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.

The core operating principle for GCAM is that of partial market equilibrium. The GCAM solution process is the process of iterating on market prices until this equilibrium is reached. GCAM is a dynamic recursive model, meaning that decision-makers do not know the future when making a decision today: 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.

GCAM uses a global climate carbon-cycle climate module, Hector, 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.).

TIAM Grantham v.3.2 The TIMES Integrate Assessment Model, TIAM, is an optimisation model. It is the multi-region, global version of TIMES, which provides a technology-rich basis for estimating how energy system operations will evolve over a long-term, multiple-period time horizon (Loulou et al., 2005). It performs a cost-minimisation 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 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.

TIAM simultaneously calculates the quantity of production and consumption of the different energy 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 computes a market-clearing of the energy systems and operates on a perfect foresight principles.

The model tracks the three main sources of GHGs—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); emissions are sent to the climate module, which calculates changes in the atmospheric concentration of CO_2, CH_4, and N_2O.

MUSE. MUSE, the ModUlar energy system Simulation Environment, is a simulation-based modelling environment for the assessment of how national or multi-regional energy systems might change over time (Giarola et al., 2021). 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, as shown in recent applications of the model (García Kerdan et al., 2019).

MUSE calculates a partial equilibrium on the energy system using a market clearing algorithm based on a recursive dynamic approach and built over an agent-based framework. It consists of modular independent agent-based sector modules, joined together by a market clearing algorithm, which 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. Each sector module is based on a bottom-up technology rich model. Investments and operations in novel technologies depend on how agents would sort them depending on objectives, goals, and preferences. The model calculates the three main sources of GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Modelling of policies is implemented through 4 types of actions. Minimum capacities for selected technologies are estimated considering increments to the total capacity until the limit is met; from the start year of a policy linear increments apply from a year to the next. Minimum shares of low-carbon technologies are estimated setting minimum capacities of the selected technologies in a region until the share of the activity equals the policy target; from the start year of a policy linear increments apply from a year to the next until the target is met. Fuel efficiency or emission standards in the transport sector are regulated for new vehicles implying that gradual transformations of the energy system would occur; from the start year of a policy linear increments apply from a year to the next until the target is met. Emission limits are applied with an endogenously escalating carbon price.

Model 42. Model 42 is a simulation model used to calculate the impacts of possible structural changes, as well as of improvements in the efficiency of energy use (Shirov et al., 2016) for 50 countries and country-regions into which the world is represented. The energy sector is described in detail in the form of energy balances, synchronised with the International Energy Agency 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. The model runs up to 2045 using a yearly time step.

The model uses a bottom-up approach ot the energy systems modelling. First the model calculates the final consumption of energy resources for industry, transport, the residential sector, and services. Then, it calculates the necessary amount of primary energy resources needed to produce the required petroleum products, electricity, and heat. The amount of primary energy consumption is multiplied by the carbon intensity vector and thus CO_2 emissions associated with the energy sector are calculated.

Modelling of policies is implemented through 3 types of actions. In the power sector, the target values of low-carbon energy sources were achieved by varying their shares in the total electricity generation structure in reference years in accordance with the adopted policies. Fuel efficiency parameters in the transport sector are regulated mainly for new car sales, while the model considers the average actual fuel efficiency in the sector. Therefore, for the average fuel consumption, the expected long-term dynamics of the new vehicles standard was applied in accordance with the hypothesis that the structural transformation of the entire fleet is a process extended over time. The spread of low-carbon types of transport, by analogy with the power sector, occurred through the variation of their share in the total vehicle fleet. Modelling of other policies (for instance, reducing the energy or carbon intensity of the economy) is performed through the "strengthening" of observable trends in the energy intensity changes (by different energy resources) of particular sectors. These groups of policies do not cover the full range, but are the most impactful. And the most significant effects from these policies are in the EU, the US, China, India, (perhaps) Canada and Australia. Since the NDC Scenario is more ambitious in terms of emissions reduction, almost the same set of measures was applied for it, but in a more strong and rapid manner.

GEMINI-E3 v.7.0. 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 model (Bernard and 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. Goods of the same sector produced by different countries can be substituted according to the Armington elasticity of substitution.

For each sector and region, GEMINI-E3 computes total demand as the sum of final demand (investment, consumption, and exports) and intermediate consumptions. 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.

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 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.

In terms of policies, all the included ones 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. The policies have been implemented sequentially which required several iterations, as some climate policies may overlap each together. 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.

ICES-XPS v.1.0. The Intertemporal Computable Equilibrium System (ICES) is a recursive-dynamic multi-regional Computable General Equilibrium model developed to assess economy-wide impacts of climate change on the economic system and to study mitigation and adaptation policies. The model follows the GTAP-E model (Truong et al., 2007), and contains a detailed representation of the electricity sector, extended with recursive dynamic features and a more detailed representation of the government split into two agents (i.e. government and private households) (Eboli et al., 2010).

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 Sustainable Development Goals (SDG) indicators.

The model accounts 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. For each productive sector, a typical firm maximises its profits given a set of input (factors and intermediate inputs) and output prices. Consistent with neoclassical theory, the production technology assumes constant returns to scale. Each commodity is sold domestically or abroad following the Armington approach. 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.

The model's economic database is complemented with satellite databases on energy volumes and CO_2 energy-related emissions.

In terms of policies, the Emission Trading Scheme (ETS) for the ETS sectors (energy, industry) was implemented in EU28. The emission quota was set for the entire EU28 and it was achieved trading emission permits across countries at a common carbon price (endogenous). For the non-ETS sectors, it was imposed a country-specific domestic cap on emissions that allowed to determine endogenous national prices for those emissions. For China, India and Chile, targets were set on emission intensity deriving endogenously the carbon prices. For all other countries with NDC targets, emission caps were imposed and computed endogenously the national carbon taxes. EU28 and South Korea targets on renewable energy share were achieved through dedicated subsidies.

E3ME v.6.1. 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. The entire globe is broken down into 69 regions.

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. 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.

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. 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.

E3ME covers fourteen types of air-borne emissions: CO_2, CH_4, N_2O, F-gases; land-use CO_2 (exogenously); and particulate matter (BC, OC, PM2.5), sulphur oxides (SOx), other nitrogen oxides (NOx), and organic compounds.

In terms of policies into scenarios (including the model baseline), the model includes mainly the IEA Current and Stated Policies and European Commission's projections. 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.

Appendix B. Additional data

Table B.6
Summary statistics of European population projections. Population in million of inhabitants. The *Dependency Ratio* is defined as the ratio between population either younger than 15 or older than 65 over the population in its working age. The *Child dependency ratio* is defined as the ratio between the population up to 15 years of age (included) over the population in its working age. The *Old dependency ratio* is defined as the ratio between the population older than 65 over the population in its working age.

Variable	European Commission (2017)	European Commission (2020)	KC and Lutz (2017)
Total population in 2030	524.1	520.7	532.3
Total population in 2050	528.4	523.7	544.1
Working age population in 2030	319.7	320.6	325.7
Working age population in 2050	299.2	298.9	300.7
Dependency ratio in 2050	76.6%	75.2%	80.9%
Child dependency ratio in 2050	26.2%	25.3%	24.8%
Old dependency ratio in 2050	50.4%	49.9%	56.1%

Table B.7
Summary of the techno-economic harmonisation approach applied to the power sector.

Internal parameter	Benchmarking parameter	benchmarking databases
Capital costs (USD’10 per kW)	Capital Costs (EUR’15 per kW)	Mantzos et al. (2017)
O&M costs (USD’10 per kW)	ratio of O&M over capital costs (EUR’15 per kW)	Mantzos et al. (2017)
Lifetime (years)	Lifetime (years)	Mantzos et al. (2017)
Capacity factor	Capacity factor	Mantzos et al. (2017)

Table B.8
Summary of the techno-economic harmonisation approach applied to the transport sector.

Internal parameter	Benchmarking parameter	benchmarking databases
Capital costs increase (USD’10 per B-vkm)	Capital Costs (EUR’15 B-vkm)	Napp et al. (2019), Jadun et al. (2017)
O&M costs (USD’10 per B-vkm)	O&M costs (EUR’15 per B-vkm)	(Mantzos et al., 2017), Napp et al. (2019), Jadun et al. (2017)
Lifetime (years)	Lifetime (years)	Napp et al. (2019)
Efficiency	Efficiency	Napp et al. (2019)

Table B.9
Summary of the techno-economic harmonisation approach applied to the industrial sector. The technologies included are integrated with CCS. Benchmark technologies are the corresponding technologies in cement and steel without CCS. Sources: (Gardarsdottir et al., 2019), (Voldsund et al., 2019).

Internal parameter	Benchmarking parameter	Values
Capital costs (USD’10 per product-yr)	capital cost increase from standard	85% in 2020 65% from 2030
O&M costs (USD’10 per product-yr)	percentage of annualised capital costs	10%
Energy penalty	energy penalty from standard	32%
Capture rate	on reaction and combustion emissions	90%

Table B.10
Summary of the harmonisation approach applied to the residential and commercial building sector. Technologies included: space cooling, space heating, water heating, cooking facilities, lighting, other appliances. Standard technologies are used as benchmark.

Internal parameter	Benchmarking parameter	benchmarking databases
Capital costs (USD'10 per PJ-yr)	capital cost deviation from standard (EUR'15 kW)	Mantzos et al. (2017)
O&M costs (USD'10 per PJ-yr)	O&M cost deviation form standard (EUR'15 per kW)	Mantzos et al. (2017)
Efficiency	efficiency deviation from standard	Mantzos et al. (2017)

Table B.11
Switch year between short-term and long-term for the "Rest of the countries in the OECD database" in the updated GDP and population projections.

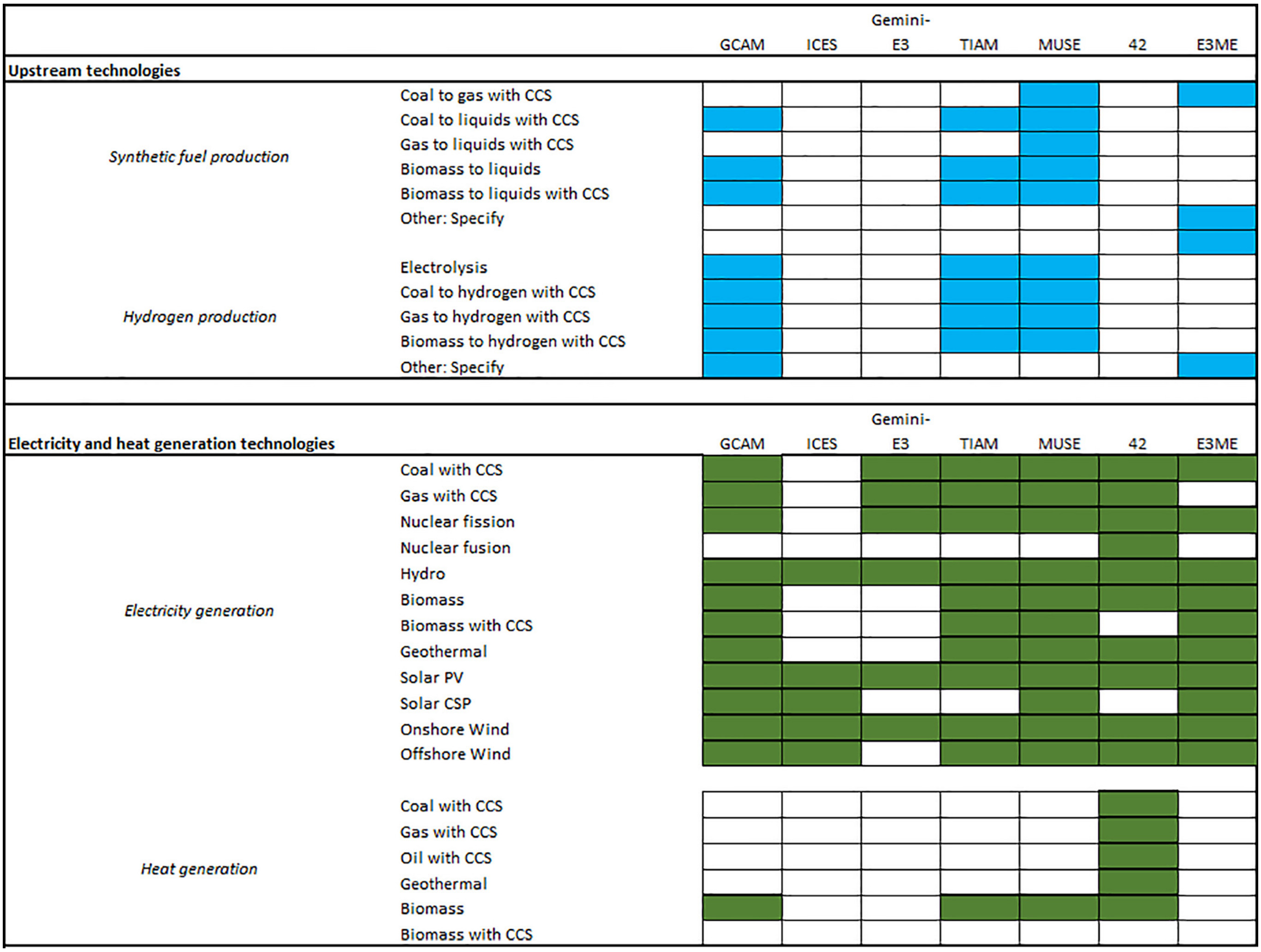
Country	Population growth	GDP growth
Australia	2026	2025
Canada	2037	2037
Chile	2060	2060
Iceland	2023	2025
Israel	2026	2027
Japan	2026	2026
Korea	2035	2032
Mexico	2061	2061
New Zealand	2061	2061
Switzerland	2038	2036
Turkey	2050	2051
United States	2031	2031
Argentina	2050	2051
Brazil	2061	2061
China (People's Republic of)	2036	2036
Colombia	2021	2025
Costa Rica	2035	2036
India	2037	2037
Indonesia	2035	2035
Saudi Arabia	2061	2043
South Africa	2039	2039

Table B.12
Comparison of population (expressed in millions) used in PARIS REINFORCE (PR) with other sources, such as the United Nations Population Prospects (UN), OECD projections for population, and SSP2 assumptions (KC and Lutz, 2017).

Regional aggregation	Source	2020	2030	2050	2100
World	UN	7795	8548	9735	10,875
	SSP2	7614	8264	9166	8999
	PR	7736	8431	9361	9224
OECD	OECD	1364	1421	1475	
	UN	1364	1406	1444	1395
	SSP2	1365	1432	1518	1506
	PR	1363	1427	1505	1498
BRICS	OECD	3493	3681	3787	
	UN	3511	3700	3813	3219
	SSP2	3437	3608	3716	2967
	PR	3495	3683	3757	2895

Table B.13
Comparison of GDP (in Million US dollars) used in PARIS REINFORCE (PR) with other sources, such as the OECD projections and SSP2 Dellink et al., 2017). GDP projections have been calculated as growth rates starting from model and region dependent values for 2010. BRICS stand for Brazil, Russia, India, Indonesia, China and South-Africa

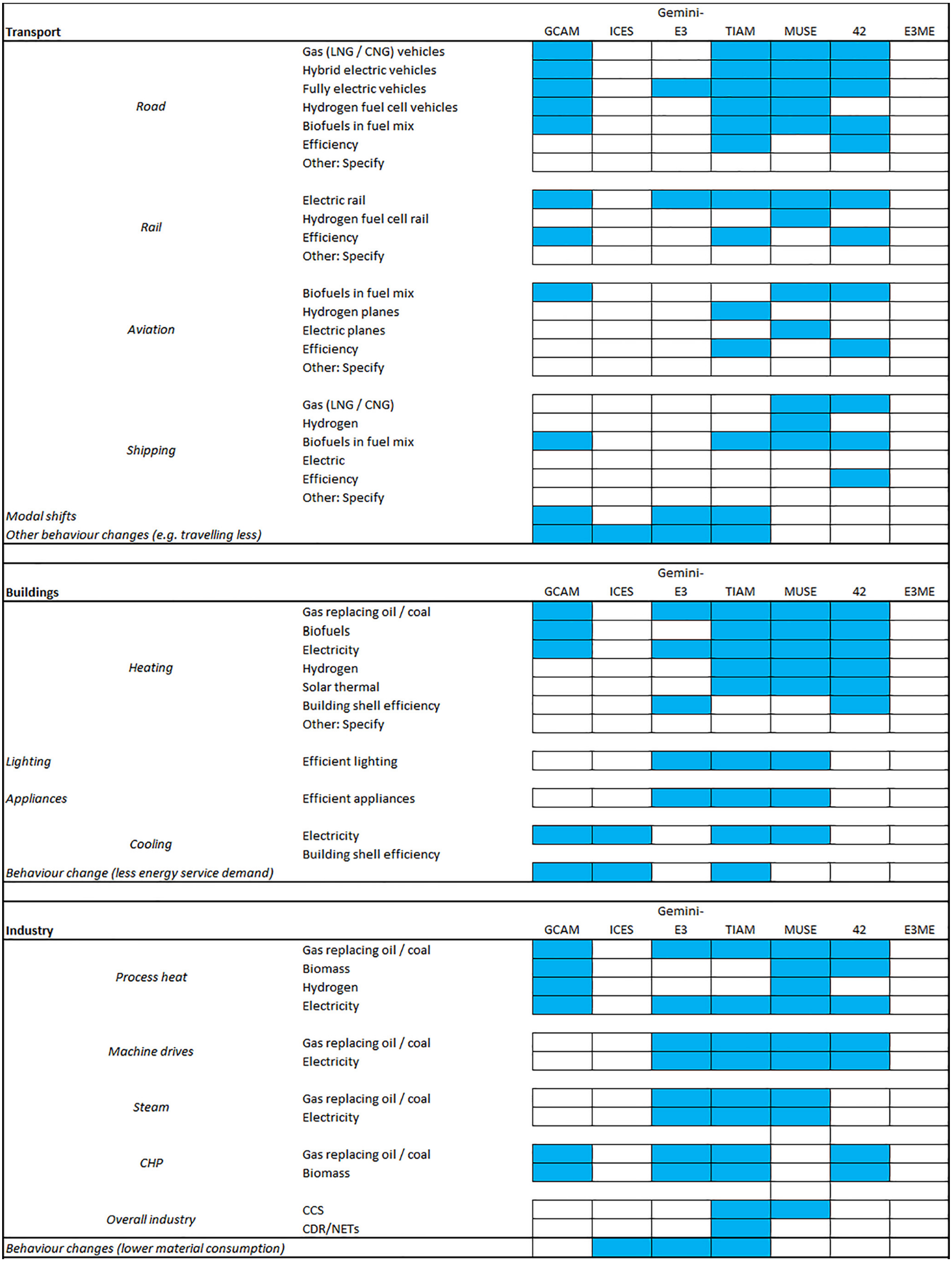
Regional aggregation	Source	2020	2030	2050	2100
OECD	OECD	54,530	65,182	94,880	
	SSP2	55,719	67,859	92,079	161,861
	PR	53,831	63,770	86,729	159,327
BRICS	OECD	49,205	74,031	128,321	
	SSP2	55,053	89,219	151,500	277,930
	PR	49,272	75,802	131,118	264,595



Upstream technologies		GCAM	ICES	Gemini-E3	TIAM	MUSE	42	E3ME
Synthetic fuel production	Coal to gas with CCS					🟦		🟦
	Coal to liquids with CCS	🟦			🟦	🟦		
	Gas to liquids with CCS					🟦		
	Biomass to liquids	🟦			🟦	🟦		
	Biomass to liquids with CCS	🟦			🟦	🟦		
	Other: Specify							🟦
								🟦
Hydrogen production	Electrolysis	🟦			🟦	🟦		
	Coal to hydrogen with CCS	🟦			🟦	🟦		
	Gas to hydrogen with CCS	🟦			🟦	🟦		
	Biomass to hydrogen with CCS	🟦			🟦	🟦		
	Other: Specify	🟦						🟦

Electricity and heat generation technologies		GCAM	ICES	Gemini-E3	TIAM	MUSE	42	E3ME
Electricity generation	Coal with CCS	🟩		🟩	🟩	🟩	🟩	🟩
	Gas with CCS	🟩		🟩	🟩	🟩	🟩	
	Nuclear fission	🟩		🟩	🟩	🟩	🟩	🟩
	Nuclear fusion						🟩	
	Hydro	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Biomass	🟩			🟩	🟩	🟩	🟩
	Biomass with CCS	🟩			🟩	🟩		🟩
	Geothermal	🟩			🟩	🟩	🟩	🟩
	Solar PV	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Solar CSP	🟩	🟩			🟩		🟩
	Onshore Wind	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Offshore Wind	🟩	🟩		🟩	🟩	🟩	🟩
Heat generation	Coal with CCS						🟩	
	Gas with CCS						🟩	
	Oil with CCS						🟩	
	Geothermal						🟩	
	Biomass	🟩			🟩	🟩	🟩	
	Biomass with CCS							

Fig. B.6. Model inter-comparison: technology mapping in the supply sector. “42” refers to model 42.



Transport		GCAM	ICES	Gemini-E3	TIAM	MUSE	42	E3ME
Road	Gas (LNG / CNG) vehicles	■			■	■	■	
	Hybrid electric vehicles	■			■	■	■	
	Fully electric vehicles	■		■	■	■	■	
	Hydrogen fuel cell vehicles	■			■	■		
	Biofuels in fuel mix	■			■	■	■	
	Efficiency				■		■	
	Other: Specify							
Rail	Electric rail	■		■	■	■	■	
	Hydrogen fuel cell rail					■		
	Efficiency	■			■		■	
	Other: Specify							
Aviation	Biofuels in fuel mix	■				■	■	
	Hydrogen planes				■			
	Electric planes					■		
	Efficiency				■		■	
	Other: Specify							
Shipping	Gas (LNG / CNG)					■	■	
	Hydrogen					■		
	Biofuels in fuel mix	■			■	■	■	
	Electric							
	Efficiency						■	
	Other: Specify							
Modal shifts		■		■	■			
Other behaviour changes (e.g. travelling less)		■	■	■	■			

Buildings		GCAM	ICES	Gemini-E3	TIAM	MUSE	42	E3ME
Heating	Gas replacing oil / coal	■		■	■	■	■	
	Biofuels	■			■	■	■	
	Electricity	■		■	■	■	■	
	Hydrogen				■	■	■	
	Solar thermal				■	■	■	
	Building shell efficiency			■			■	
	Other: Specify							
Lighting	Efficient lighting			■	■	■		
Appliances	Efficient appliances			■	■	■		
Cooling	Electricity	■	■		■	■		
	Building shell efficiency							
Behaviour change (less energy service demand)		■	■		■			

Industry		GCAM	ICES	Gemini-E3	TIAM	MUSE	42	E3ME
Process heat	Gas replacing oil / coal	■		■	■	■	■	
	Biomass	■				■	■	
	Hydrogen	■				■		
	Electricity	■		■	■	■	■	
Machine drives	Gas replacing oil / coal			■	■	■	■	
	Electricity			■	■	■	■	
Steam	Gas replacing oil / coal			■	■	■		
	Electricity			■	■	■		
CHP	Gas replacing oil / coal	■		■	■		■	
	Biomass	■		■	■		■	
Overall industry	CCS				■	■		
	CDR/NETs				■			
Behaviour changes (lower material consumption)			■	■	■			

Fig. B.7. Model inter-comparison: technology mapping in the demand sector. “42” refers to model 42.

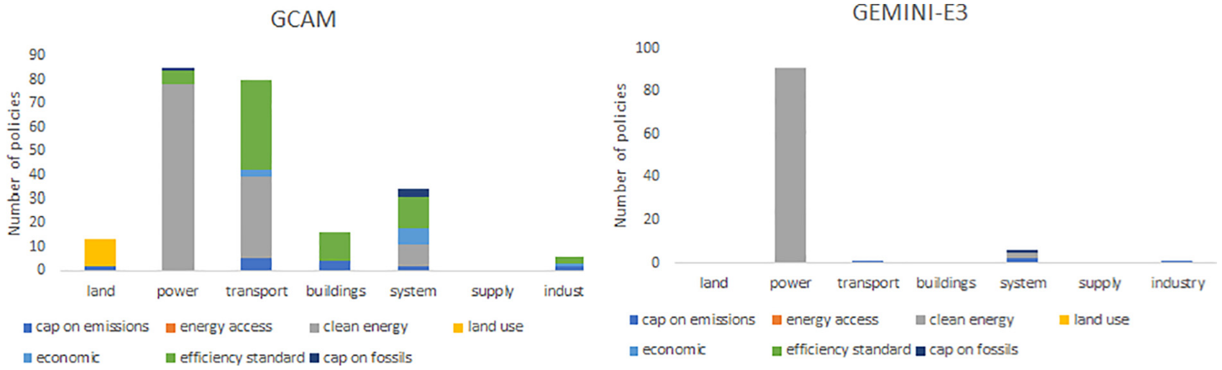


Fig. B.8. Breakdown of policies implemented in GCAM and GEMINI-E3.

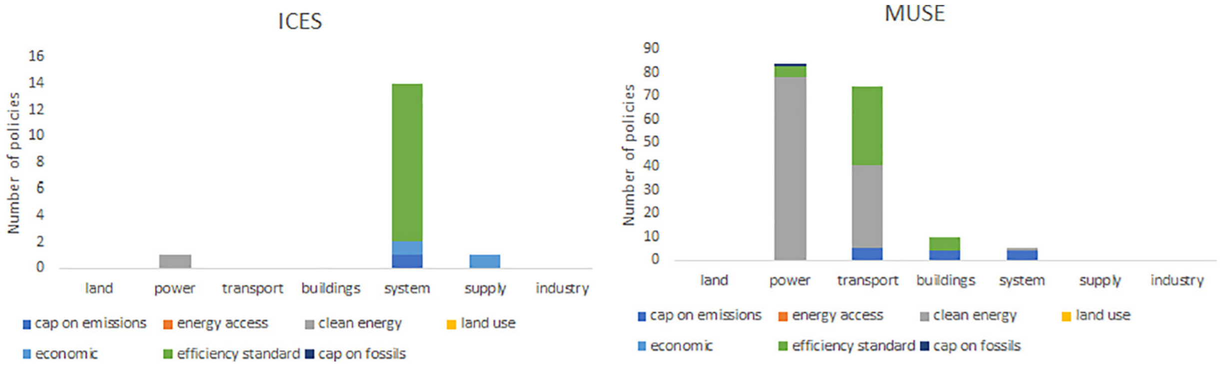


Fig. B.9. Breakdown of policies implemented in ICES-XPS and MUSE.

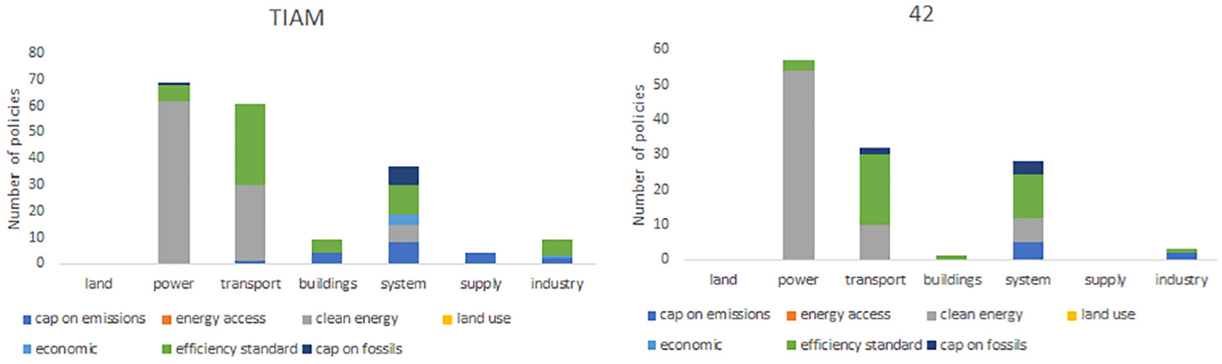


Fig. B.10. Breakdown of policies implemented in TIAM and model 42.

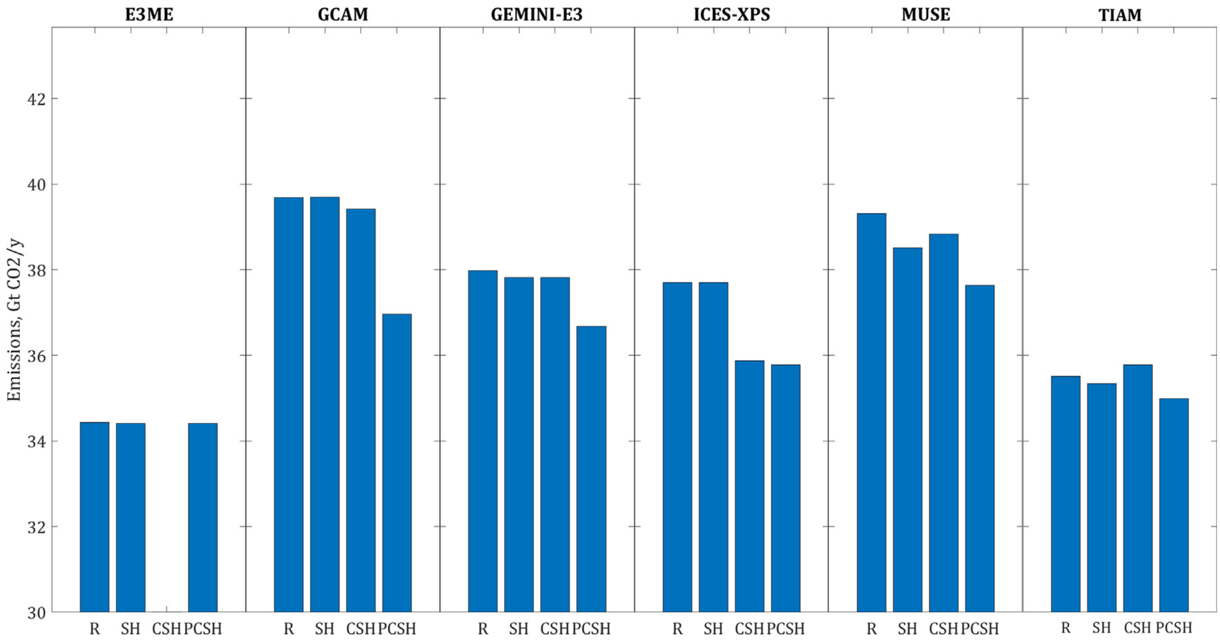


Fig. B.11. Global emissions in 2020 from the models, Gt of CO_2/y.

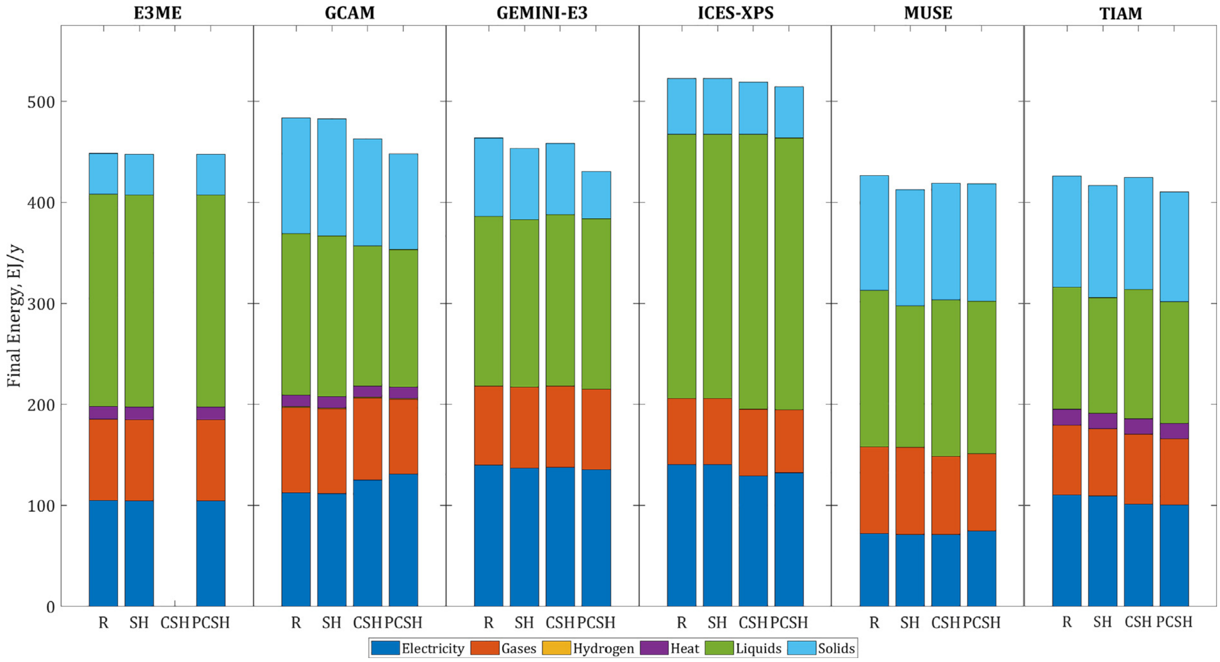


Fig. B.12. Final energy in 2020 from the models, EJ/y.

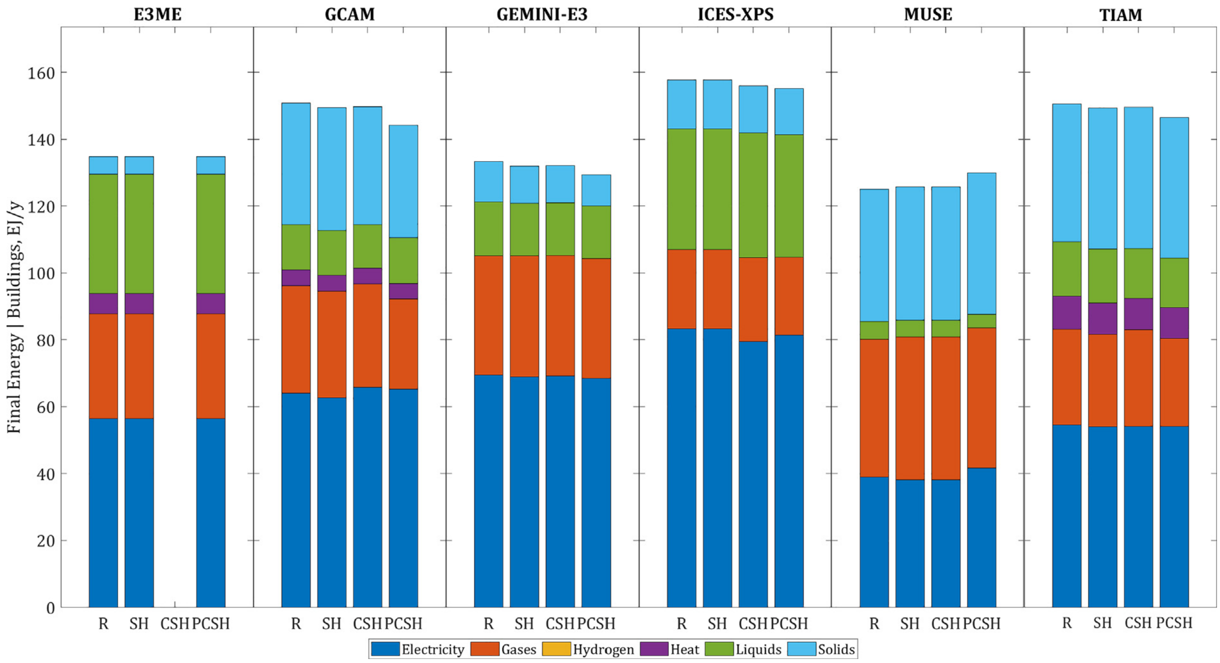


Fig. B.13. Final energy in buildings in 2030 from the models, EJ/y.

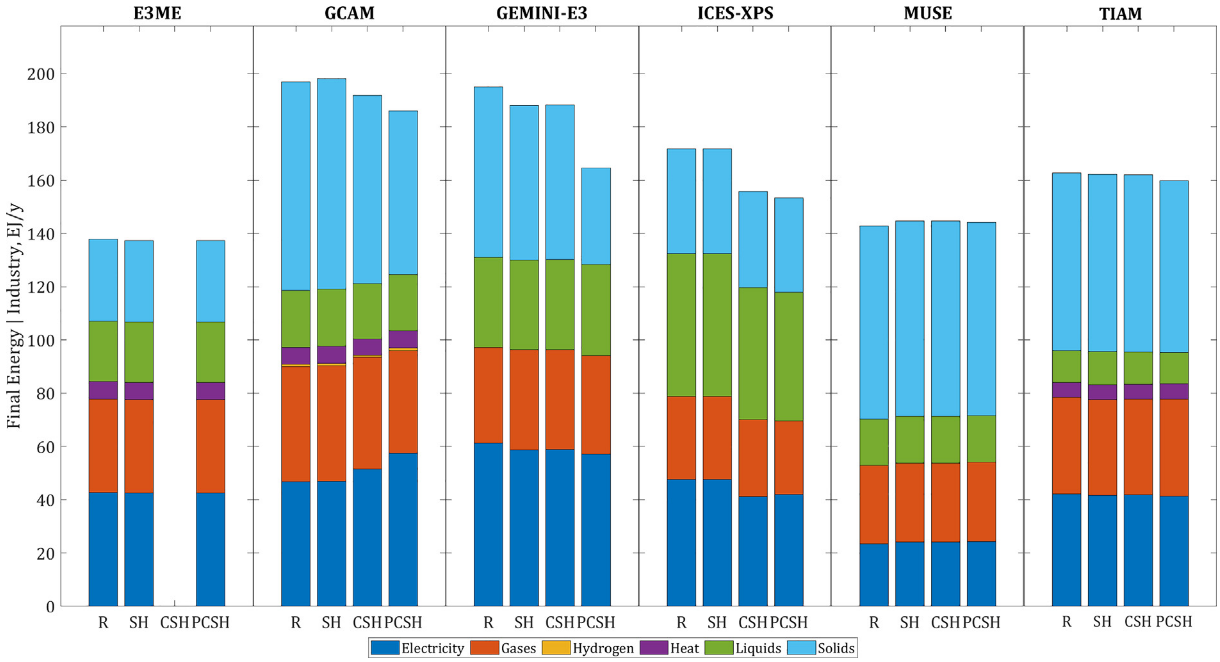


Fig. B.14. Final energy in industry in 2030 from the models, EJ/y.

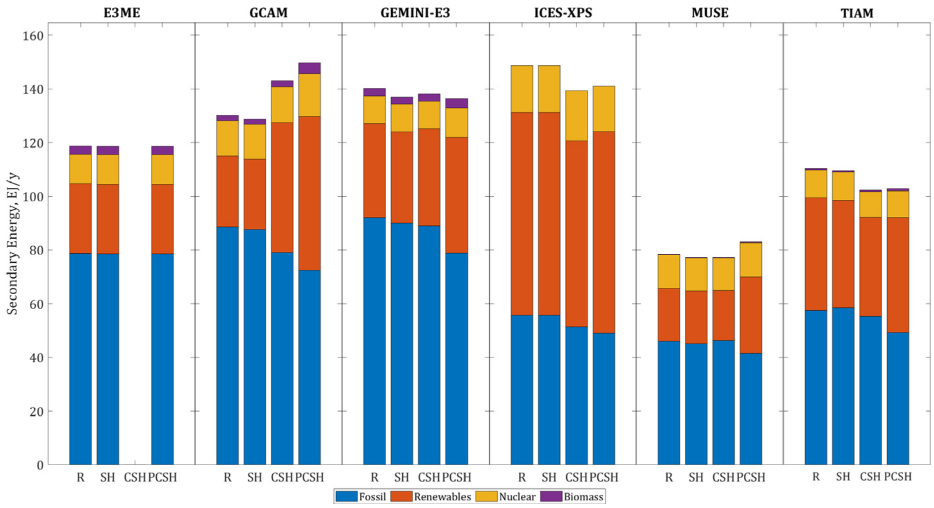


Fig. B.15. Power generation in 2030 from the models, EJ/y.

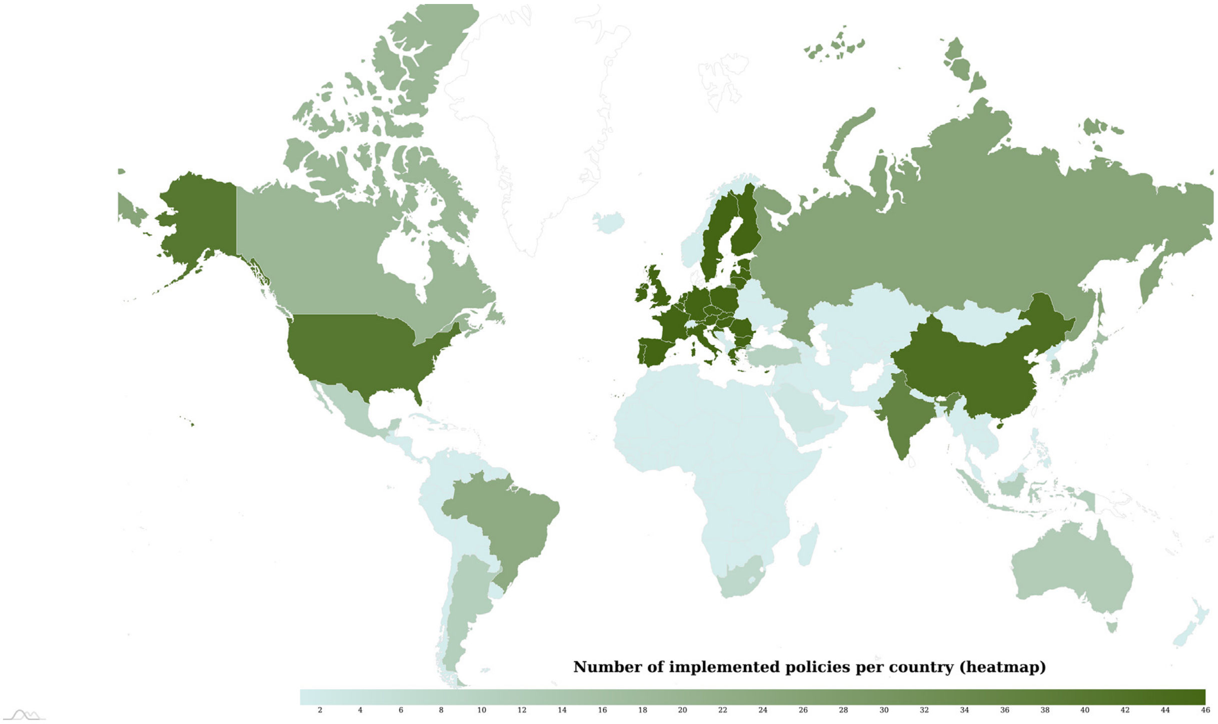


Fig. B.16. Regional mapping of the policy database.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.146861.

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