IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

D3.4 - An outline of planned interlinkages among models, analyses, and scenarios

WP3 – Exchanging – Open & FAIR science, mutual learning

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Responsible Author	Ilkka Keppo		**Email**	ilkka.keppo@aalto.fi
	Aalto		**Phone**	+358 50 5781103
Contributors	Hesam Ghadaksaz, Behzad Zamanipour [Aalto]; Jan Ivar Korsbakken [CICERO]; Ajay Gambhir [Imperial]; Natasha Frilingou, Alexandros Nikas [NTUA]			
Reviewer(s)	Dirk-Jan van de Ven [BC3]; Georg Holtz [WI]; Matteo Vincenzo Rocco [POLIMI], Konstantinos Koasidis [NTUA], Jakob Thellufsen [AAU]			
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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This deliverable will feed into the development of the modelling and scenario framework for the first modelling cycle. It will additionally serve as the basis for developing a more generalised process for the second modelling cycle of the project.

3. Short summary of results (<250 words)

Linking models to other models provides a way of expanding the boundaries of the analysis, but often requires solving difficult problems and even after that comes with trade-offs. This deliverable provides an analysis starting from how different models and their capabilities are characterised, then uses such model typologies to link IAM COMPACT models to the preliminary research questions collected in the stakeholder mechanism before finishing with a discussion about the various issues that should be considered when designing the linking strategy. The aim of this work is to feed into the next steps of the scenario and research question development process, and to the development of a generalised model linking process flow for the second modelling cycle.

4. Evidence of accomplishment

This report.

Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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Executive Summary

Linking models to other models provides a way of expanding the boundaries of the analysis, but often requires solving difficult problems and even after that comes with trade-offs. This deliverable provides an analysis starting from how different models and their capabilities are characterised, then uses such model typologies to link IAM COMPACT models to the preliminary research questions collected in the stakeholder mechanism before finishing with a discussion about the various issues that should be considered when designing the linking strategy. The aim of this work is to feed into the next steps of the scenario and research question development process, and to the development of a generalised model linking process flow for the second modelling cycle.

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1 Introduction and context

Model linking is a common, almost routine activity, in many scenario exercises. It provides a way of expanding the system boundaries of the modelling and therefore brings more interlinked elements within the endogenous assessment. It also helps to mitigate increasing the complexity of individual tools: Linking provides a light weight option to expanding the scope of an individual tool, e.g. linking a potentially already existing land use model to an energy system model, rather than expanding the energy system model to also include dynamic modelling of the full land use system. Model linking typically involves the exchange of a limited number of outputs between the models and iterating the linked model system until a convergence criterion of some kind has been reached. The linking exercise may also include some harmonisation, but this is rarely exhaustive.

While providing clear benefits for analysis, model linking also implies trade-offs and creates new problems to be solved. The more technical considerations range from deciding e.g. how to treat inconsistencies in temporal, spatial and variable definitions, system boundaries (including significant background assumptions) and model overlaps, different foresights for the modelled decisions, level of harmonisation, convergence criteria and technical implementation of the data exchange. There often are no easy, obvious solutions to many of these, and several of such problems are likely to be present in most linking exercises. As compromises will thus need to be made, understanding the implications of the specific ones made is of key importance. This leads to the second area of trade-offs; the changing interpretation of the model outcomes. Individual models have been built internally consistent, following e.g., a specific foresight and decision-making rationale that can be fairly easily explained also outside the model context. For the linked model system this is not necessarily true, as the model linking often breaks the internally consistent decision-making rationale of individual models. This is further complicated by the compromises made in the linking, as they will also feed into the results.

The aim of this deliverable is to feed into the policy response mechanism (PRM) and provide information for choosing which models could be used together, and in what way, to answer specific research questions identified through the PRM. In this first cycle, we lay the groundwork for a structured process, or a toolbox, for assessing model linkages, to be fully developed for the second cycle of PRM. We will start by reviewing the state of the art for model linking and typology in Section 2. The latter is important for understanding what the models include endogenously, and how they should be interpreted, informing both model choice for a specific research question as well as model linking. In Section 3 we will first describe the models available in IAM COMPACT, before analysing, from the perspective of what is required of the models, the preliminary research questions that have emerged from the early stages of the PRM. We conclude in Section 4 by providing some generalised notes about what should be considered in the model and scenario linking process, considering the preliminary questions as well as later, once the finalised research questions have become available.

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2 Review of the state of the art

In this section we will first provide a short review of chosen papers, all putting more than usual focus on the linking itself. This aims to provide us with a starting point for considering various aspects of the model linking in this project. We follow this with a review and discussion of model typologies. Model typologies are attempts to describe and compare models through a subset of their key characteristics. The typologies thus aim to find the most important dimensions in which the models can meaningfully differ, and in doing so also provide useful information for model choice and linking.

2.1 Model linking

The significance of model linking stems from our desire to understand the world as a system that consists of various sub-systems and the relationships between them. In this way, modellers try to connect different models, each of which describes one or multiple sub-systems, in order to capture their effects on each other. Model linking can also assist the modellers in their journey to analyse the functionality of socio-ecological systems by connecting different disciplines. The alternative to model linking, to build one single model covering all connected sub-systems, has its own downsides, considering the level of detail required by the variety of stakeholders who need solutions for their, often sub-system specific questions (Verburg et al., 2016).

Model linking has been used to expand the model coverage and thus deepen our knowledge in the interlinked areas such as energy demand, geospatial dimensions, macroeconomics, social and behavioural sciences, and environmental and earth sciences (Chang et al., 2023). The linking has been established in different ways which can be categorised into three categories; soft-linked, hard-linked, and integrated models. Soft-linking refers to user-controlled data exchange between the models, hard-linking is defined as a formal computer-led transfer of information with shared code from the models, and the integrated models are the combination of models running and handling data as one (Helgesen & Tomasgard, 2018). Soft-linking has been used often across energy system models, while the other two approaches are less common (Chang et al., 2023).

While the necessity and advantages of model linking are clear, the practical implementation of the linking is often complicated. Many studies have adopted model linking to reinforce their analyses, however, few of them have focused on the process of model linking itself and its technical aspects. The technical problems are mainly around variable definitions and system boundaries, harmonisation, convergence, model foresight, temporal and spatial scales, and implementation of the data exchange.

The first step in model linking is to identify the points at which both models are going to be linked. These points are referred to as connection points in some studies (Krook-Riekkola et al., 2017). A connection point can be defined as the point where an endogenous variable in one model is fed into the other model as an exogenous parameter. The identification of connection points can only happen when the modeller has a clear understanding of the differences and similarities between the models. The call for providing guidance for model linking has always been present. As an example, the general soft-linking approach for linking macroeconomic and energy system models has been proposed in 1996 (Wene, 1996), however, without providing information about the sector-level linking variables. A recent study discusses a soft-linking process between a Computational General Equilibrium (CGE) model and an energy system model, and on top of that, communicates both negative and positive experiences (Krook-Riekkola et al., 2017). The study also used multiple what they call "direction-specific connection points" (DSCPs), which had not, according to the study, been used in previous studies. DSCPs are partial solutions to inconsistencies between how two different models describe sectors, e.g. due to aggregation, and mean that data transfer from model A to model B is addressed separately, even for the same sector. For instance, what does it mean that a sector is growing in one model in comparison to the corresponding sector growth in the other model, considering the different interpretations of the sectors in the two models? Or what should one do in order to resolve the problem of non-matching sector classifications? They brought two examples of such problems. In the first one, the pharmaceutical industry has been considered as a stand-alone sector in one model, and aggregated to a general chemicals sector in the other one. Due to the different aggregation levels, the own-price elasticities of energy demand differ across the models which consequently results in linking difficulties. The second example is about the transport sector, which is described through different transport segments in the energy system model, whereas in the CGE model, it is, in addition to transport sectors, also embedded also in other sectors (e.g. through household consumption). Considering the difficulties of achieving consistency, the direction-specific approach could be helpful in the sense that for each direction one could identify which result in one model can improve the specific input assumption of the other model. The linking process has followed a step-by-step process. The first step is identifying basic differences between the models, the second one is to identify the overlaps and the final step is deciding upon common exogenous variables. Regarding the overlaps, one could see which model has a higher level of detail on the area which is being assessed in order to decide which model should govern those variables. Also, there might be some exogenous variables that are input to one model and output from the other model. This type of variable can similarly be soft-linked (Krook-Riekkola et al., 2017).

Some common exogenous variables may exist that need to be harmonised between the two models. Usually, the harmonisation concentrates on aligning the scenario narratives within each model which includes harmonisation of assumptions on socio-economic development metrics, techno-economic characteristics of technologies, and other scenario-specific considerations. The values of these variables could already be set based on different statistic sources. However, sometimes variables can't be fully harmonised due to the differences in the models and the level of detail embedded in them. For example, Krook-Riekkola et al. (2017) could not harmonise the biomass prices as their CGE has a limited description of biomass resources while the energy system model describes the biomass resources in detail. The harmonisation process itself has been discussed in a clear and transparent manner (Giarola et al., 2021). Although they did not link models, they proposed a framework for a harmonisation methodology with several steps and recommendations to reduce the variance of the results of various models. This approach consists of multiple steps and has also been adopted in the PARIS REINFORCE project.

One of the other issues that arise in the process of linking two models is the difference in their temporal resolution and model foresight. This problem is commonly observed when a power market model and an energy system model are to be linked. The power market models typically require a higher temporal resolution compared to that needed in energy system models and the former also includes factors such as ramping, start-up costs, minimum up time, etc. This type of linkage can be split into unidirectional and bidirectional linkages. In a unidirectional linkage, a set of information from the energy system model is fed into the power market model without any feedback to the energy system model. For bidirectional linkage, some decisions from the power market model are also used as input to the energy system model. In this case, there could be iteration between the two models until they converge (Seljom et al., 2020).

In Deane et al. (2012) the former method was used to test the feasibility and performance of the electricity generation capacity and electricity consumption mix from an energy system model in a power market model. The authors linked a PLEXOS power market model to the Irish TIMES model in order to evaluate the power generation portfolio and its technical feasibility. They concluded that although the energy system model provides a reliable power system, it undervalues flexible elements and underestimates wind curtailment. This approach is used to verify the feasibility of the less detailed model and not to improve the quality of the results. For instance, a unidirectional linkage does not consider if an investment in the energy system model should be modified or not due to operational barriers. The latter method has been rarely utilised which is due to its complexities (Fidje et al., 2009; Pina et al., 2013; Rosen et al., 2005; Seljom et al., 2020). The recent study by Seljom et al. (2020) tried not to exclude parts of the energy system unlike previous studies, and presented a transparent linking methodology with a clearly defined convergence criterion.

The convergence is yet another crucial aspect of model linking. Depending on the model linking practice, one might seek convergence while iterating between two, or more, models. Some of the studies do not iterate between the models they linked, or at least are not transparent about their convergence criterion, but a handful of studies have mentioned the criteria on which they seek convergence. For instance, Krook-Riekkola et al. (2017) did not define a convergence criterion owing to the large set of connection points between their two models. In contrast, in a recent study, a multi-model integrated assessment of European energy pathways has been done through various means, firstly by linking modelling tools iteratively in some cases, secondly harmonising the model assumptions in others, and finally only comparing model outputs in the rest. For example, in a specific part of the study pan-European TIMES energy systems model and the global Computable General Equilibrium NEWAGE were iteratively linked, considering the change in the value of GDP as the convergence criterion (Gardumi et al., 2022).

The incompatibility of spatial scales between two models can cause many issues in model linking. For overcoming this challenge, some downscaling and upscaling methods might be applied (Rizzati et al., 2022). It is also possible to add the spatial detail to the model that is lacking it. For instance, in order to incorporate the spatial details into the energy system models, Geographic Information System (GIS) tools have been used to pre-process the spatial data which can be fed into the energy system models, and also post-process the results of such models. The GIS tools can help the energy system models to overcome different challenges such as the identification of regional potential, selection of appropriate sites for new capacities, selection of the best routes for transmission and the best sites for distribution substations, and identification of site-specific demand patterns. To enhance the outcomes of conventional energy system planning, GIS is also employed to determine the best locations and investment plan sizes. For instance, in one application of this linkage, an iterative process of data exchange between a GIS tool and an energy system model has led to finding the optimal shares of on- and off-grid electricity generation in rural areas (Rocco et al., 2021). The linkage between an energy system model and a GIS tool could, however, be cumbersome as it increases the complexity of the model and results in a high computational burden (Aryanpur et al., 2021). As a solution, some studies have only focused on the use of GIS tools in a specific sector (Petrović & Karlsson, 2016; STRACHAN et al., 2009).

Finally, the implementation of the data exchange in model linking can be a challenge. There have been some efforts to resolve this issue, such as a simulation model integration framework (simf) that has been developed to support coupling and running the infrastructure simulation models as a system of systems (Usher & Russell, 2019). At the same time, the mere need for such a framework underlines the non-triviality of carrying out the practical part of model linking and integration.

2.2 Model typology

Many modelling and analysis tools have been developed to guide decision-makers in making robust short- and long-term policy decisions to address the complex challenges facing energy, and other, systems. Due to the complexity of the challenges faced, each tool was created to respond to specific policy questions, or at least take its own angle on it. Accordingly, modelling and analysis tools have been brought with their distinctive capabilities and gaps.

Several research activities have been done to identify and reflect the different capabilities and gaps across various modelling tools. The activities of cataloguing and classifying modelling tools have taken various scopes. Model documentation cataloguing various tools, in particular, has been an area of activity in recent years. These efforts especially aim to address worries raised with respect to transparency issues. The argument was that modelling tools, especially Integrated Assessment Models (IAMs), are not transparent enough; therefore, it is difficult to understand the context and meaning of their outputs. The Integrated Assessment Modeling Consortium (IAMC) documentation (IAMC, 2022) was an entry point to these efforts.

The IAMC wiki derives its name from the Integrated Assessment Modeling Consortium (IAMC), an organisation of scientific research institutions involved in integrated assessment modelling and analysis. The IAMC has members from all over the world who manage most of the IAM models that are currently being used. The IAMC wiki offers a framework for the transparent wiki-based documentation of these models. This makes it possible to compare these models side by side. The FP7 ADVANCE project was the leading supporter of developing the IAMC wiki.

Similarly, I^{2}AM PARIS (PARIS REINFORCE, 2022) is an open-access data exchange platform hosting detailed documentation, inputs, and outputs of modelling tools and exercises for all audiences. I^{2}AM PARIS is aimed to become the vessel of the international energy- and climate-economy modelling community. This platform provides a library of the models regarding their coverage, granularity, representation, and features. The I^{2}AM PARIS platform has been developed within the framework of the PARIS REINFORCE project, which has received funding from the European Union's Horizon 2020 Research and Innovation Program. The platform is further supported by the Horizon 2020 NDC ASPECTS and ENCLUDE projects, and the current Horizon Europe IAM COMPACT and DIAMOND projects.

Beyond the documentation-oriented research activities, several other research studies also tried to shed light on the capabilities and gaps of different modelling tools. These studies either explicitly or implicitly devise model typologies and ways in which to express differences between various tools. In doing so they also suggest either general or context-specific views about the characteristics for which differences are most meaningful and important for understanding the scope, remit, and capabilities of the tools. Reviewing various such studies, we hope to develop an overview of all the elements that have, in specific contexts, been deemed to hold such importance.

A large part of the studies was focused on capabilities and gaps for modelling and analysis of the transition complications regarding the concerns related to climate change. Among them, Connolly et al. (2010) examined different computer tools for analysing the integration of renewables in energy systems. A total of 37 tools were included in the final analysis, which was carried out in collaboration with the tool developers or recommended points of contact. Kriegler et al. (2015) tried to explain variations among policy-relevant model results by classifying models based on proposed diagnostic indicators within a study of 11 global models. Ringkjob et al. (2018) looked in depth at 75 modelling tools currently used to analyse energy and electricity systems with large shares of variable renewables. They evaluated the capabilities of a wide range of modelling tools, from small-scale electrical analysis tools to long-term global energy models. The evaluation was validated and updated by model developers or affiliated contact persons Savvidis et al. (2019). did a model classification to compare a large variety of model types with a focus on models for electricity markets in light of low-carbon policies. After clustering the diverse issues concerning decarbonisation, they tried to measure the suitability of energy models for answering particular issues. Fattahi et al. (2020) reviewed the features and gaps of current energy system models regarding several key criteria. Based on the review, they described 7 low-carbon energy system modelling challenges. Keppo et al. (2021) briefly summarised the landscape of Integrated assessment models (IAMs) and how these models differ from each other. In their discussion of six prominent critiques of IAMs, they reflected on the use and capabilities of diverse IAMs against those critiques. Blanco et al. (2022) classified different models developed to assess the energy systems accounting for the unique characteristics of hydrogen. This review identified 124 categories commonly used to map models. Després et al. (2015) intended to see how the characteristics of the power sector are integrated into the broader energy modelling tools. They proposed comparing criteria for classifying five modelling tools for the power sector. Also, previous Assessment Reports by Intergovernmental Panel on Climate Change (IPCC) identified the need to improve the transparency of model assumptions, following which the assessment Reports detailed the modelling frameworks. Key characteristics of applied models to the assessments are provided in related chapters.

Some other research studies focused on reviewing state-of-the-art modelling practices for a specific country or a group of countries. Beeck (1999) attempted to provide guidelines to facilitate the selection of suitable energy models for local energy planning in developing countries. Nine ways were proposed in which energy models could be classified. Urban et al. (2007) assessed the inclusion of the main characteristics of developing countries in energy models. They discussed the main characteristics, focusing mainly on developing Asia, and presented a model comparison of 12 selected energy models. Hall and Buckley (2016) developed a classification schema to compare energy system models and tools available in the United Kingdom. All referred models are presented, and 22 models are classified in the developed schema. Laha and Chakraborty (2017) identified the significant factors to be considered for developing an energy model for India. The benefits, challenges, and need for energy models have been documented in this study through a comparative survey of fifteen energy models. Lopion et al. (2018) reviewed national energy system models that incorporate all energy sectors and can support governmental decision-making processes. The models are evaluated in the context of the region and time in which they were developed to identify modelling trends. Musonye et al. (2020) provided a scoping review of the previous modelling studies on energy systems for Sub-Saharan Africa (SSA). They reviewed 30 energy modelling studies on the SSA region regarding their features and covered policy themes by each model. Rhodes et al. (2022) reviewed the key improvements, knowledge gaps, and critiques of energy-economy models in Canada. They assessed 21 models against four criteria for assessing the ability of energy-economy models to evaluate climate policy impacts. Plazas-Niño et al. (2022) presented a systematic literature review of the accurate tools to guide decision-making in national energy planning. Their study covered the major energy system optimisation models, involved data, trends in scenario analysis for decarbonisation pathways, and the challenges associated with the reviewed models.

In addition, some studies did a review of modelling practices at a local level. Manfren et al. (2011) presented a selection of models currently available for urban distributed production planning and design. They analysed the modelling tools not only from a theoretical perspective but also from an application perspective. Klemm and Vennemann (2021) tried to determine and examine the general features of energy system models. They surveyed 145 different energy system models to identify those models having the required characteristics for modelling district energy generation at the city level. Bouw et al. (2021) provided an analysis of the model characteristics needed for application in the built environment at the local scale. By assessing various models, they mapped the models against the identified characteristics to help select the best approaches for modelling exercises.

Besides, some research studies tried to shed light on new trends in the development of modelling tools. Venturini et al. (2018) reviewed and classified integrated energy and transport models according to the methodology used for introducing the main transport-related behavioural features focusing on technology choice, modal choice, driving pattern, and new mobility trends. Oberle and Elsland (2019a) provided an overview of the existing Open Access Models (OAMs) used for energy system analysis. They typified the OAMs based on their different degrees of accessibility and also characterised them according to predefined criteria. Prina et al. (2020) identified the resolution issue as one of the main challenges regarding modelling tool development. They proposed a classification of bottom-up energy system modelling tools. According to the proposed classification, 22 existing bottom-up energy system models have been reviewed and categorised. Chang et al. (2021) surveyed 54 energy system modelling tools directly from model developers and users. The survey results presented key features and trends in tool development. Aly et al. (2022) performed a literature review of 183 publications that apply modelling to analyse multiple or single SDGs. They presented a multi-dimensional model classification scheme that enables an understanding of how models contribute to achieving the SDGs.

To summarise the review, we will aggregate the information from the reviewed papers into a combined summary typology schema. The schema is meant to be comprehensive, to show the various ways in which modelling tools and their capabilities could be differentiated in various contexts. This schema could also provide insights into how models could vary inter- and intra-dimensions. This will facilitate the proper selection and linking procedure of the models to address the proposed policy questions within the IAM COMPACT project. Using the developed typology schema helps understand the current modelling capabilities and identify the limitations in addressing the policy questions.

It should be noted that the categorisation dimensions are not entirely independent, as we have aimed to retain as much variety in the dimension definitions as possible. Some aggregation into dimensions has been done, though, so that the same or similar elements in different studies show under the same dimensions. In our presentation we have separated the proposed dimensions into different clusters of (i) temporal and spatial granularity, (ii) sectoral dynamics, (iii) approach and methodology, (iv) accessibility, and (v) others, each collected in a separate table.

The combination of dimensions and elements under the dimensions could show how a model is designed and could be used to address a policy question. It needs to be noted, however, that other layers often exist under the named elements, listing e.g. the countries covered (under Spatial coverage, National) or industrial subsectors and/or technologies (under Energy, industry). This underlines the importance of considering such typology information for a given model as the first step in establishing the remit of the model, to be followed by a more detailed dialogue with the modelling team. Finally, as removing as little information as possible comes with the trade-off of using the table, we've added a table with more consolidation across the elements to the annex.

Table 1. Modelling typology schema in the cluster of temporal and spatial granularity

Dimension	Elements
Temporal resolution (Blanco et al., 2022; Bouw et al., 2021; Chang et al., 2021; Connolly et al., 2010; Després et al., 2015; Fattahi et al., 2020; Hall & Buckley, 2016; IAMC, 2022; Klemm & Vennemann, 2021; Lopion et al., 2018; Oberle & Elsland, 2019b; Plazas-Niño et al., 2022; Prina et al., 2020; Ringkjøb et al., 2018; Savvidis et al., 2019; Venturini et al., 2018)	Instantly; Hourly; Monthly; Seasonal; Annual; Multi-year
Temporal horizon (Aly et al., 2022; Beeck, 1999; Blanco et al., 2022; Bouw et al., 2021; Chang et al., 2021; Connolly et al., 2010; Després et al., 2015; Hall & Buckley, 2016; IAMC, 2022; Klemm & Vennemann, 2021; Kriegler et al., 2015; Lopion et al., 2018; Musonye et al., 2020; Oberle & Elsland, 2019b; Plazas-Niño et al., 2022; Ringkjøb et al., 2018; Savvidis et al., 2019; Venturini et al., 2018)	Short-term (up to 1 year); Long-term (up to 100 years); From a base year to a horizon year
Spatial coverage (Aly et al., 2022; Beeck, 1999; Blanco et al., 2022; Bouw et al., 2021; Chang et al., 2021; Connolly et al., 2010; Fattahi et al., 2020; Hall & Buckley, 2016; IAMC, 2022; IPCC, 2022; Keppo et al., 2021; Klemm & Vennemann, 2021; Laha & Chakraborty, 2017; Lopion et al., 2018; Manfren et al., 2011; Musonye et al., 2020; Oberle & Elsland, 2019b; PARIS REINFORCE, 2022; Plazas-Niño et al., 2022; Prina et al., 2020; Ringkjøb et al., 2018; Savvidis et al., 2019; Venturini et al., 2018)	Global; Regional; National; State/Multi-state; Local
Spatial resolution (Blanco et al., 2022; Fattahi et al., 2020; IAMC, 2022; Keppo et al., 2021; Klemm & Vennemann, 2021; Laha & Chakraborty, 2017; Lopion et al., 2018; Plazas-Niño et al., 2022; Prina et al., 2020; Savvidis et al., 2019)	Number of nodes

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Table 2. Modelling typology schema in the cluster of accessibility

Dimension	Elements
Development environment (Blanco et al., 2022; Lopion et al., 2018; Pfenninger et al., 2018; Ringkjøb et al., 2018)	GAMS + Solver; Vensim; Python; Windows with .NET; MySQL; R; Excel/VBA; Fortran; GNU MathProg; AMPL; MATLAB; AIMMS; C++; PHP
User interface (Chang et al., 2021)	Graphical user interface; Web-based user interface; Direct coding and programming; GUI with the possibility of coding if needed
Training requirements (Blanco et al., 2022)	Low; Medium; High
Users (Chang et al., 2021; Connolly et al., 2010; Fattahi et al., 2020)	Used by academics; Used by governments/public officials; Used by NGOs; Used by private/commercial users. Very high number of users; High number of users; Medium number of users; Low number of users
Data availability (Bouw et al., 2021; Fattahi et al., 2020; Keppo et al., 2021)	No data; Generalised open-source global data; Limited country-specific data; Detailed open-source global data; Detailed country-specific datasets
Data requirements (Beeck, 1999; Blanco et al., 2022; Hall & Buckley, 2016)	Qualitative; Quantitative; Monetary; Aggregated; Disaggregated
Licensing (Blanco et al., 2022; Bouw et al., 2021; Chang et al., 2021; Connolly et al., 2010; Fattahi et al., 2020; Keppo et al., 2021; Klemm & Vennemann, 2021; Lopion et al., 2018; Manfren et al., 2011; Oberle & Elsland, 2019b; Pfenninger et al., 2018; Plazas-Niño et al., 2022; Ringkjøb et al., 2018)	Open source; Open-source upon request; Commercial; Proprietary; Copyleft; Permissive

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Table 3. Modelling typology schema in the cluster of sectoral dynamics

Dimension	Elements
Climate components and complexity (IPCC, 2023)	Atmosphere; Ocean; Sea Ice; Land Surface; Biosphere; Ice Sheets; Sediment and Weathering
Climate indicators (IAMC, 2022; Kriegler et al., 2015; Laha & Chakraborty, 2017)	Concentration; Radiative forcing; Temperature change; Sea level rise; Ocean acidification
Mitigation, removal, and adaptation measures (IPCC, 2022; PARIS REINFORCE, 2022)	Demand-side measures; Supply-side measures; AFOLU measures; Carbon dioxide removal; Carbon capture and usage; Adaptation; Behavioural Changes; Buildings; Industry; Agriculture; LULUCF; Synthetic fuel production; Hydrogen production; Electricity generation; Heat generation; Road; Rail; Aviation; Shipping; Modal shifts
Energy/ considered energy sectors/ inclusion of technologies (Beeck, 1999; Blanco et al., 2022; Bouw et al., 2021; Chang et al., 2021; Connolly et al., 2010; Hall & Buckley, 2016; IAMC, 2022; IPCC, 2022; Klemm & Vennemann, 2021; Kriegler et al., 2015; Manfren et al., 2011; Plazas-Niño et al., 2022; Prina et al., 2020; Ringkjøb et al., 2018)	Behaviour; Electricity technologies; Energy technology choice; Energy technology deployment; Energy technology substitutability; Freight transportation; Heat generation; Hydrogen production; Industry; Grid infrastructure; Passenger transportation; Refined gases; Refined liquids; Residential and commercial; Industry; Transportation; Buildings; Agriculture and forestry
Suitability for 100% renewable systems (Blanco et al., 2022)	Electricity; Energy
Represented commodities (Després et al., 2015; Plazas-Niño et al., 2022; Ringkjøb et al., 2018)	Electricity; Heat; Other energy forms; Hydrogen; Oil; Gas; Coal; Uranium
Policy application areas (Musonye et al., 2020)	Trade; Transmission; Renewable portfolio standards; Climate policy; Decentralised generation; Storage; Efficiency; Universal Access
Macro-economy (IAMC, 2022)	Economic sector; Trade; Cost measures; Categorisation by (social) group; Institutional and political factors; Resource use; Technological change
Economic Coverage (Kriegler et al., 2015)	Energy; Agriculture; Land use and waste; All economic agents (firms, households, government, rest of the world); Industry; Services
Socio-Economics (PARIS REINFORCE, 2022)	Demography; GDP; Employment; Investment; Public finances; Economic activity; Incomes
Socio-economic drivers (IAMC, 2022; Laha & Chakraborty, 2017)	Autonomous energy efficiency improvements; Education; Employment; GDP; Income distribution; Labor productivity; Other socio economic driver; Population; Population age structure; Total factor productivity; Urbanisation; Other socio economic driver
Land-use	Agricultural commodities; Agriculture and forestry demands; Land cover

(IAMC, 2022)	
Technology detail or granularity (Keppo et al., 2021; Oberle & Elsland, 2019b)	High; Medium; Low

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Table 4. Modelling typology schema in the cluster of approach and methodology

Dimension	Elements
Type of analysis/ coverage/ Purpose/ Description (Blanco et al., 2022; Bouw et al., 2021; Hall & Buckley, 2016; Manfren et al., 2011; Urban et al., 2007)	Economy; Energy; Power; Environment; Climate
Equilibrium type/ Economic coverage/ Economic approach (Keppo et al., 2021; Kriegler et al., 2015; Plazas-Niño et al., 2022; Rhodes et al., 2022)	Partial equilibrium; General equilibrium ; Other
Typology (Després et al., 2015)	Optimisation; Simulation; General equilibrium models; Energy–Environment–Economy; Integrated assessment models
Tool type (Connolly et al., 2010)	Scenario; Equilibrium; Top-down; Bottom-up; Operation optimisation; Investment optimisation; Simulation
Model type (IAMC, 2022)	Integrated assessment model; Energy system model; CGE; CBA-integrated assessment model
Model coupling (Chang et al., 2021)	Soft-linked; Hard-linked; Integrated
Model type (Aly et al., 2022)	System dynamics; Agent-based; Bayesian networks; Economic; Econometric; Integrated; Knowledge-based; Mathematical quantitative; Network
Analytical approach/ Characteristics/ Model perspective (Beeck, 1999; Blanco et al., 2022; Després et al., 2015; Hall & Buckley, 2016; Lopion et al., 2018; Musonye et al., 2020; Oberle & Elsland, 2019b; Plazas-Niño et al., 2022; Ringkjøb et al., 2018; Savvidis et al., 2019; Urban et al., 2007; Venturini et al., 2018)	Top-down; Bottom-up; Hybrid
Solution method/ Methodology/ Treatment of decision making/ Type of use and capabilities/ Analytical method (Beeck, 1999; Blanco et al., 2022; Bouw et al., 2021; Chang et al., 2021; Hall & Buckley, 2016; IAMC, 2022; Klemm & Vennemann, 2021; Laha & Chakraborty, 2017; Lopion et al., 2018; Manfren et al., 2011; Musonye et al., 2020; Oberle & Elsland, 2019b; Plazas-Niño et al., 2022; Savvidis et al., 2019; Urban et al., 2007; Venturini et al., 2018)	Optimisation; Simulation; Accounting; Econometric; Economic Equilibrium
General purpose (Blanco et al., 2022; Hall & Buckley, 2016; Plazas-Niño et al., 2022)	Prediction; Forecasting; Exploratory; Backcasting

Solution horizon/ Modelling approach/ Optimisation problem approach/ transformation path analysis (Blanco et al., 2022; IAMC, 2022; Kriegler et al., 2015; Lopion et al., 2018; Plazas-Niño et al., 2022; Prina et al., 2020)	Recursive dynamic (myopic); Intertemporal optimisation (foresight)
Energy demand representation (Chang et al., 2021; Plazas-Niño et al., 2022; Ringkjøb et al., 2018)	Static demand; Elastic demand; Endogenous demand
Uncertainty analysis (Blanco et al., 2022)	Deterministic; Stochastic; Possibilistic
Uncertainty treatment (Aly et al., 2022)	No uncertainty treatment; Basic error reporting; Express uncertainty
Representation of uncertainty (Savvidis et al., 2019)	Yes; No
Treatment of uncertainty (Laha & Chakraborty, 2017)	none; uncertainty; variability; stochasticity; cultural Perspectives
Mathematical formulation/ Programming technique (Beeck, 1999; Blanco et al., 2022; Hall & Buckley, 2016; Klemm & Vennemann, 2021; Laha & Chakraborty, 2017; Plazas-Niño et al., 2022; Prina et al., 2020; Savvidis et al., 2019)	(Non) linear programming; Mixed-integer programming; Fuzzy logic
Solution method (Keppo et al., 2021)	Inter-temporal optimisation; Simulation; Recursive dynamic; (Non) linear programming; Macro econometric simulation
Methodology (Prina et al., 2020)	Simulation; Dispatch optimisation; Single objective investment optimisation; Multi-objective investment optimisation
Methodology (Ringkjøb et al., 2018)	Simulation; Linear programming; Mixed integer programming; Partial Equilibrium; Accounting; Agent-based simulation; Mixed integer quadratically constrained programming; Computable general equilibrium; Equilibrium; Covariance matrix adaptation evolution strategy; Heuristic optimisation; Economic computable equilibrium; Stochastic dual dynamic programming
Cost measures/ Cost scope (Blanco et al., 2022; Hall & Buckley, 2016; IAMC, 2022; Kriegler et al., 2015; Plazas-Niño et al., 2022; Ringkjøb et al., 2018; Savvidis et al., 2019; Venturini et al., 2018)	GDP loss; Welfare loss; Consumption loss; Area under MAC; Energy system cost mark-up; CO_2 costs

Resource use (IAMC, 2022; Kriegler et al., 2015)	Fixed; supply curve; process model
Technology choice, diffusion and sunsetting (Fattahi et al., 2020; IPCC, 2022; Keppo et al., 2021; Kriegler et al., 2015)	Logit substitution; Constant elasticity of substitution; Lowest marginal cost w/ expansion constraints; Technology choice depends on agents' preferences; Technologies w/o constraints or marginal cost w/ expansion constraints. Single capital stock with fixed lifetime and load factor, early retirement via a reduction in load factor possible; Capital vintaging with fixed lifetime and load factors, early retirement of vintages or reduction in load factors possible; Single capital stock with fixed lifetime and load factor, without early retirement; Mix of the above for different technologies
Technology learning (Blanco et al., 2022; Savvidis et al., 2019)	One-factor learning curve; Two-factor learning curve; Multi-Cluster Learning; Multi-Regional Learning
Technological Change (Kriegler et al., 2015; Rhodes et al., 2022)	Exogenous; Endogenous; Partly endogenous
Technology choice (Venturini et al., 2018)	Intangible costs/benefits, Hurdle rates; (Nested) Multinomial logit model; Disutility costs; Nested CES; Logit model
Discounting method/ rate (IAMC, 2022; IPCC, 2022; Kriegler et al., 2015)	Exogenous; Endogenous
Characteristics of baseline/ benchmark setup (IPCC, 2022; Kriegler et al., 2015)	Well-functioning markets in equilibrium; Regulatory and/or pricing policies; Socioeconomic costs & benefits of climate change impacts; Physical impacts of climate change on key processes
Capital vintaging and sunsetting of technologies (IPCC, 2022; Kriegler et al., 2015)	Single capital stock with fixed lifetime and load factor, early retirement via a reduction in load factor possible; Capital vintaging with fixed lifetime and load factors, early retirement of vintages or reduction in load factors possible; Single capital stock with fixed lifetime and load factor, without early retirement; Mix of the above for different technologies
Social parameters (Fattahi et al., 2020)	Demand curves; Agent-based models

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Table 5. Modelling typology schema in the cluster of others

Dimension	Elements
Represented electricity markets (Blanco et al., 2022; Plazas-Niño et al., 2022; Ringkjøb et al., 2018; Savvidis et al., 2019)	Spot markets; Balancing markets; Capacity market; Future market
Evaluated policies (IAMC, 2022; Keppo et al., 2021; Kriegler et al., 2015; PARIS REINFORCE, 2022; Rhodes et al., 2022; Savvidis et al., 2019)	Emission tax; Emission pricing; Cap and trade; Fuel taxes; Fuel subsidies; Feed-in-tariff; Portfolio standard; Capacity targets; Emission standards; Energy efficiency standards; Agricultural producer subsidies; Agricultural consumer subsidies; Land protection; Pricing carbon stocks
Evaluated SDGs (Aly et al., 2022; PARIS REINFORCE, 2022)	SDGs 1-16
Evaluated GHGs and pollutants (IAMC, 2022; IPCC, 2023; Kriegler et al., 2015; PARIS REINFORCE, 2022; Plazas-Niño et al., 2022; Ringkjøb et al., 2018)	CO_2 energy; CO_2 industrial processes; CO_2 land-use change; CH_4 fossil (combustion); CH_4 fossil (fugitive and process); CH_4 biogenic; N_2O; HFCs; PFCs; SF_6; SO_2; Black carbon; Organic carbon; Non-methane volatile organic compounds

3 Overview of models and policy questions

In this section we will first present the models available in the IAM COMPACT project, first summarising each tool briefly and adding existing typology information of the tools. The data and descriptions for our models come from the I^{2}AM PARIS platform and data from D4.1. We then continue to analyse a subset of the preliminary research questions from the Policy Response Mechanism, from the perspective of model requirements, and then map them against the typology information we have about the tools. This continues from the model matching work done for D4.1, by expanding the scope from policy/policy instrument-focused analysis to a broader reflection of the various ways in which model capabilities can be defined.

3.1 IAM COMPACT model portfolio

A brief description of various IAM COMPACT modelling tools is provided in the following paragraphs. After presenting the brief description of the models, the I^{2}AM PARIS platform is concisely introduced, and the work from D4.1 on mapping the capabilities of models is presented.

3.1.1 Brief description of the models

The models within the project form a diverse portfolio of global and regional integrated assessment models, energy and electricity models, as well as sectoral models. The descriptions are extracted from the I^{2}AM PARIS platform, as well as from some past applications of the models.

AIM/Enduse India (SLIM-India)

The Asia-Pacific Integrated Model/Enduse is a bottom-up and recursive dynamic model of technology selection within a country's energy economy environment system (Vishwanathan et al., 2021). Energy and material flow through technology systems in an economy, and consequent emissions, are modelled elaborately. The selection of technologies takes place in a linear optimisation framework where system cost is minimised under several constraints like the satisfaction of service demands, availability of energy and material supplies, and other system constraints. The model can perform calculations simultaneously for multiple years, and various scenarios, including policy countermeasures, can be analysed in AIM/Enduse. AIM/Enduse India versions 1.0 and 2.0 were built in the late 90s and early 2000s.

BLUES

The Brazilian Land Use and Energy System (BLUES) model is a perfect-foresight optimisation model for Brazil built on the MESSAGE (Model for Energy Supply Strategy Alternatives and Their General Environmental Impacts) platform (Rochedo et al., 2018). The model is designed to create competition between technologies and energy sources to meet the demand for exogenous food and energy services to minimise the system's total cost. BLUES comprises six native regions, where one is a main overarching region into which five sub-regions are nested. Between 2010 and 2050, BLUES optimises the energy system in five years intervals. Each representative year is divided into 12 representative days (one for each month) of 24 representative hours.

With more than 1,500 technologies tailored for each of its six native regions, the energy system is detailed across the energy transformation, transport, and consumer sectors. Cement, ceramics, chemicals, food and beverage, iron and steel, metallurgy, mining, alloys, pulp and paper, textiles, and a collection of other industries make up the industrial sector's 11 specific sub-sectors.

Calliope

Calliope is a well-known open-source energy modelling framework for building energy system models (Pfenninger & Pickering, 2018). It is used to analyse systems with arbitrarily high spatial and temporal resolution and a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents. Calliope's key features include handling high spatial and temporal resolution and efficiently running on high-performance computing systems.

Euro-Calliope is a freely available instance of the Calliope framework, which models the European electricity system at a high spatial resolution. It can be built on three spatial resolutions: the continental level as a single location, the national level with 34 locations, and the regional level with 497 locations. On each node, renewable generation and balancing capacities can be built. All capacities are used to satisfy electricity demand in all locations based on historical data. Locations are connected through transmission lines of unrestricted capacity. Using Calliope, the model is formulated as a linear optimisation problem with the total monetary cost of all capacities as the minimisation objective.

CHANCE

The Climate cHange mitigAtioN poliCies and Equality (CHANCE) model is a computable general equilibrium (CGE) that includes a large amount of household microdata (Böhringer et al., 2022). It is a disaggregated multi-regional and multi-sector model that consists of information for around 200,000 households covering all EU regions, ensuring a large representation of the behaviour of European households. General Equilibrium based models provide an economy-wide analysis, allowing the user to analyse the economy as a whole and report on, for example, GDP, prices, sector production, and competitiveness. However, on the consumption side, this model often only includes a single representative agent, limiting the distributional analysis and missing the social impacts of environmental policies. CHANCE solves this limitation by integrating a large amount of data on households. The main advantage of this approach is that environmental protection can be analysed from different perspectives of equity and efficiency. Integrating microdata allows CHANCE to investigate climate protection in greater depth from both perspectives and help identify measures with progressive effects with a reasonable loss of efficiency. Furthermore, linking macro models with household microdata is an appropriate approach for evaluating the trade-off between equity and efficiency. Household microdata provides detailed information about households and the heterogeneity of different economic agents. They enable the user to widen the distributional analysis and focus on the sectors and households most affected by policies. On the other hand, macro models enable the impacts of environmental policies to be assessed from efficiency-based and macroeconomic perspectives. CHANCE is built based on the latest version of the GTAP database (GTAP 10), while the main source of microdata is the latest harmonised European Household Budget Survey, which is merged with the EU Statistics on Income and Living Conditions through statistical matching.

China-MAPLE

The China Multi-pollutant Abatement Planning and Long-term benefit Evaluation (MAPLE) is a bottom-up model based on the TIMES modelling framework (Yang et al., 2021). The TIMES modelling platform provides a technology-rich basis for estimating how energy system operations will evolve over a long-term, multiple-period time horizon. TIMES offers thus a detailed representation of energy sectors, which includes extraction, transformation, distribution, end uses, and trade of various energy forms and materials. It determines the best configuration of the energy systems to meet service demands at the lowest possible cost over a long-term horizon while adhering to GHG emission restrictions. It computes an equilibrium in energy markets (partial equilibrium).

The MAPLE model optimises the investment and operation of primary energy technologies under local constraints regarding emissions of GHGs and pollutants in China. The model can project future energy use trends in reference scenarios and other comparative scenarios of varying degrees of mitigation action. The objective of the model is the total cost of the energy system, including investment costs, residual values of assets, fixed and variable operating and maintenance costs, local energy extraction costs, the costs of energy imports beyond China, gains from exports to regions outside of China, major energy transmission and distribution costs, related taxes and additional subsidies.

CICERO-SCM

The Cicero Simple Climate Model (CICERO-SCM) is an energy balance model originally developed around 20 years ago in Fortran that has since been in continuous use and subject to minor revisions to keep up with updated best estimates in the science (Sandstad et al., 2022). It was recently used as one of a suite of emulators linking

Working Groups 1 and 3 of the IPCC 6th Assessment Report. For AR6, CICERO-SCM was tuned to reproduce the surface temperature evolution assessed by Working Group 1 and a range of other parameters. CICERO-SCM has recently been ported to Python and is being tested for public, open-source release. The base version will include tunable parameters and the possibility of running user-generated scenarios and will form the basis for several planned extensions - notably regarding short-lived climate forcers and the interaction of anthropogenic climate change with natural variability.

CLEWs

The Climate, Land, Energy, Water systems (CLEWs) is a model-based methodology to assess the costs and benefits of policy and investment decisions made in one sector (e.g., land use) on the other sectors (e.g., water supply) and thereby support policy coherence (Howells et al., 2013). CLEWs-based models can be developed with different approaches and different modelling tools. The standard way of creating a CLEWs model consists of a techno-economic representation of the climate, land, energy, and water systems within the long-term optimisation tool of OSeMOSYS. Here, the parts of these systems are represented as processes with certain transfer functions and exchange between them different commodities. The optimisation seeks to minimise the net present value of all costs incurred across the water, energy, and land sectors in the whole-time domain analysed (typically of several decades) while meeting an increasing demand for commodities (e.g., food products) and resource availability constraints. The energy sector is the one requiring the highest resolution, typically including any energy conversion and energy storage process. It can be regionalised, and some power infrastructures can be represented individually. Any emission type can be represented as long as emission factors are available and emissions are linearly dependent on generation. The land system model represents many possible types of land uses, including built-up land, forest, grassland, barren land, water bodies, other (e.g., natural reserves), pastures, and crops. Crops are further divided into any type of crop that is relevant to the region being analysed. Each crop is again divided into five categories of land uses, depending on the kind of inputs: irrigated land with intermediate or high input (in terms of fertilisers, energy, and water) and rainfed land with low, intermediate, and high input. Each type will have different yields, and they compete in the model based on cost- and resource-optimality criteria. Also, land uses are divided into clusters, which aggregate cells of the region with similar agro-climatic conditions. Emissions from land use changes are represented. Besides, the water system represents precipitation, all water inputs and outputs of land uses, and all final water uses. Precipitation, evaporation from water bodies, and evapotranspiration from vegetation are represented. They vary according to climatic conditions and climate change. Groundwater and surface water uses are described separately (but need improvement). The water system is part of the optimisation. However, it can also be represented with an accounting model externally to OSeMOSYS (e.g., using WEAP) and soft-linked with OSeMOSYS.

DREEM (TEEM)

TEEM, the TEESlab Modelling suite, is an ensemble of high-resolution energy system simulation and optimisation models consisting of (i) the Business Strategy Assessment Model (BSAM), which is an agent-based electricity wholesale market simulation considering the complex operations within a power pool central dispatch Day Ahead Market, (ii) the Agent-based Technology adOption Model (ATOM), which simulates the dynamics of technology adoption among consumers, (iii) the Dynamic high-Resolution dEmand-sidE Management (DREEM) model, which serves as an entry point in Demand-Side management modelling in the building sector, and (iv) the Adaptive polIcymaking Model (AIM), which generates real-time visualisations of adaptive policy maps, showing various sequences of policy options leading robustly to desired policy outcomes (Stavrakas et al., 2019; Stavrakas & Flamos, 2020).

The modules of TEEM can be coupled (i.e., soft- and/or hard-linked) with each other and other models/modules to support the evaluation of energy-related challenges. It can also perform a meta-analysis of other models' inputs and outputs to identify the conditions of success of a policy instrument, as well as generate robust policy pathways, by treating various modelling assumptions as potential future evolutions of policies' context.

DyNERIO

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The Dynamic Extraction and Recycling Input-Output framework (DYNERIO) is an integrated energy-economy modelling framework (Rinaldi et al., 2023). It is an Input-Output based simulation and impact evaluation model with a global geographical scope and fully characterised industrial sectors. DynERIO captures the whole economic spectrum and multiple regions based on input-output databases, which allows modelling policies in terms of (i) an increase in consumption of goods; (ii) a change of industries' productive structure (i.e., steel plants switch from coal/gas to electricity use). New production levels of energy commodities needed to fulfil the shocked economic system are tracked by the input-output table and converted into a capacity to be operative at a given year. From the information on the capacity stock evolution over time, it is possible to derive the associated net extraction of raw materials. Impact evaluation of desired policies is possible through introducing economic and environmental indicators such as gross value added, production levels of commodities and services, extracted and recycled critical raw materials, GHG emissions, water consumption, land use, and primary energy use.

The DYNERIO framework comprises three soft-linked modules, each devoted to specific tasks. Module 1, named Multi-Regional Input-Output (MRIO) module, works as a standard Leontief linear system of algebraic equations (quantity and price models). Once the underlying empirical Input-Output dataset is defined, future scenarios are implemented as exogenous changes in yearly final demand and technology structure based on future population trends, living standards, and prospective technology changes. The model then derives goods and services production yields by sector/product, including the number of energy carriers and services (e.g., transport service, electricity, heat, etc.) and regional and sectoral impact indicators (value added generation, energy use, emissions, etc.). Module 2, named Technology Capacity Stock (TCS) module, consists of a linear optimisation model to quantify the yearly installed, operating, and disposed of capacity stock of energy technologies necessary to satisfy the yearly total energy demand quantified by Module 1. Module 3, named Dynamic Extraction and Recycling (dynER) module, consists of a system of algebraic difference equations, modelling the regional operation of supply chains of critical materials and those devoted to producing the related energy systems. Such a module receives the total capacity stock of technologies as an exogenous parameter. It determines extracted, recycled, and traded critical materials among regions in the analysed scenario based on technical data related to the supply chains of critical materials and the related energy technologies.

EDM Industry

The Energy Demand model (EDM) is a model family out of which two models are part of the portfolio of IAM COMPACT: EDM Industry EU and EDM Global Steel[1]. The EDM Industry is a tool to analyse possible future industrial production systems and explore consistent pathways to getting there. A technologically detailed bottom-up methodology is used to design the pathway for target achievement. EDM Industry EU model consists of three interconnected modules of (1) EDM-S as a material flow analysis tool, (d) EDM-I optimising the investments, and (3) EDM-D, which is a bottom-up calculation of CO_2 and energy demand. Regarding non-energy-intensive industries, the EDM Industry EU model considers activity-based modelling at the country level and extrapolates energy demands based on economic indicators, efficiency parameters, and technology shifts.

The EDM Global Steel model is used to analyse possible futures of the global steel sector (divided into 20 countries/ regions, including EU-27). The main outputs of the model are the final energy demand and GHG emissions per country/region, as well as investment costs. The model is an Excel and R-based scenario development tool built on national or regional targets, scenarios and/or technology roadmaps while integrating all those into a global picture. National/regional pathways can be modified to explore global implications, for example, to develop various Paris-compatible global pathways and to explicate their respective national/regional underpinning.

EnergyPLAN

EnergyPLAN (Lund et al., 2021; Østergaard et al., 2022) is an energy systems analysis tool created for research and study in the development of future sustainable energy solutions, with a particular focus on energy systems

[1] https://www.i2am-paris.eu/detailed_model_doc/wisee-edm

with high percentages of renewable energy sources (Østergaard, 2015). EnergyPLAN was established to take advantage of the synergies made possible by encompassing the entire energy system. As a result, the user of EnergyPLAN can adopt an all-encompassing strategy while concentrating on the analysis of cross-sectoral interaction. Energy commodities connect disparate demand sectors, including transportation, industry, and the built environment, with supply technology. As a result, EnergyPLAN makes it possible to analyse the conversion of renewable power into various energy sources, such as heat, hydrogen, green gases, and electro fuels, as well as implement energy efficiency upgrades and energy conservation.

EnergyPLAN was specifically created to enable the design and simulation of energy systems that utilise renewable energy sources. Thus, it operates with a one-hour temporal resolution for an entire year and has sectorial integration in its core to act as an enabler of integrating renewable energy sources into the energy system. It is a simulation model based on analytical programming, implying that EnergyPLAN employs pre-coded priorities and procedures to handle the behaviour of all units in each time step.

EXPANSE

The EXploration of PAtterns in Near-optimal energy ScEnarios (EXPANSE) is a bottom-up spatially explicit and technology-rich electricity system model (Trutnevyte, 2013). The unique feature of EXPANSE is that it applies the Modelling to Generate Alternatives method (MGA) to compute and analyse large numbers of cost-optimal and near-optimal scenarios with only a single set of assumptions. The principle of MGA is to relax the cost-optimality assumption and instead define an acceptable range of total system costs to search for scenarios within this acceptable range. Thus, EXPANSE tackles the common critiques of other bottom-up technology-rich models by not only focusing on costs as the sole driver of the energy transition. In this way, EXPANSE also allows tackling structural uncertainty better, reduces the modeller's bias, and provides various alternative scenarios for policymakers.

Based on the exogenous assumption, such as technology parameters and costs, electricity demand, or maximum acceptable increase in total system cost, EXPANSE generates a wanted set of maximally different scenarios that are within the pre-defined level of acceptable costs. For each computer-generated scenario, EXPANSE assesses the implications on the key decision-relevant outcomes for European regions, such as technology capacity and operation, cost, employment, greenhouse gas and particulate matter emissions, land use, regional inequality, and so on. EXPANSE is then combined with the Monte Carlo technique to quantify the associated uncertainties. In this way, the critical application of EXPANSE is to provide more realistic what-if scenarios of the electricity sector transition driven by costs and other socio-technical factors.

FaIR

The Finite Amplitude Impulse Response (FAIR) model tracks the time-integrated airborne fraction of carbon and uses this to determine the efficiency of carbon sinks, calculating atmospheric CO_2 concentrations, radiative forcing, and temperature change (Smith et al., 2018). Then, FaIR produces global mean temperature projections from various forcers. FAIR v1.0 is well-calibrated to the earth system model's temperature and carbon cycle response. FAIR v1.3 is extended to calculate non-CO_2 greenhouse gas concentrations from emissions, aerosol forcing from aerosol precursor emissions, tropospheric and stratospheric ozone forcing from the emissions of precursors, and forcings from black carbon on snow, stratospheric methane oxidation to water vapour, contrails and land use change. Forcings from volcanic eruptions and solar irradiance fluctuations are supplied externally. These forcings are then converted to a temperature change, taking into account the different thermal responses of the ocean mixed layer and deep ocean.

The model philosophy in FAIR is to represent these processes simply to be able to emulate the historical radiative forcing time series in AR5 given input emissions. FAIR is written in Python and is open-source.

GCAM/ GCAM-USA

The Global Change Analysis Model (GCAM) is a global dynamic-recursive long-term model with technology-rich representations of the economy, energy, land use, and water sectors linked to a climate model that can be used to explore climate change mitigation policies, including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology (Luckow et al., 2010). Regional population and labour productivity growth assumptions drive the energy and land-use systems employing numerous technology options to produce, transform, and provide energy services, make agriculture and forest products, and determine land use and cover. Using a run period extending from 1990 to 2100 at 5-year intervals, GCAM has been used to explore the potential role of emerging energy supply technologies and the greenhouse gas consequences of specific policy measures or energy technology adoption. Outputs include projections of future energy supply and demand and the resulting greenhouse gas emissions, radiative forcing, and climate effects of 16 greenhouse gases, aerosols, and short-lived species at 0.5×0.5 degree resolution, contingent on assumptions about future population, economy, technology, and climate mitigation policy. GCAM has been developed at PNNL for over 20 years and is now a freely available community model.

GCAM-USA is a version of GCAM with 50 state-level resolutions in the United States. GCAM-USA is embedded within the global GCAM model, so conditions within the United States are internally consistent with international situations. While primary fossil energy production in GCAM-USA is modelled at the aggregate national level, energy transformation and end-use demands are modelled at the individual state level. GCAM-USA includes state-level emissions of air pollutants.

Hector

Hector is an open-source, object-oriented, simple global climate carbon-cycle model that runs quickly while still representing the most critical global scale earth system processes (Hartin et al., 2015). Hector is a simple climate model (SCM, also known as a reduced-complexity climate model), a highly versatile class with many applications. Due to their computational efficiency, SCMs can easily be coupled to other models and used to design scenarios, emulate more complex climate models, and conduct uncertainty analyses.

Hector has a three-part primary carbon cycle of a one-pool atmosphere, land, and ocean. The model's terrestrial carbon cycle includes primary production and respiration fluxes, accommodating arbitrary geographic divisions into, e.g., ecological biomes or political units. Hector actively solves the inorganic carbon system in the surface ocean, directly calculating air-sea fluxes of carbon and ocean pH. Hector reproduces the global historical trends of atmospheric CO_2, radiative forcing, and surface temperatures.

OSeMOSYS

The Open Source energy Modelling SYStem is a fully (data to the solver) open-source long-term bottom-up optimisation framework for energy systems modelling. It calculates the annual energy mix that minimises the total net present costs of the whole system while meeting exogenously defined energy-related demands and complying with constraints dictated by resource availability, technical characteristics of technologies, and introduced policies. It is a partial equilibrium modelling tool that can be used with either perfect or myopic foresight. It allows high temporal (up to hourly) and spatial resolution. Its modelling paradigm is close to MESSAGE and TIMES.

MAGICC

The Model for the Assessment of Greenhouse Gas Induced Climate Change is a prime reduced-complexity model, often used by the IPCC for crucial scientific publications and by several Integrated Assessment Models (Meinshausen et al., 2011). MAGICC has a hemispherically averaged upwelling-diffusion ocean coupled to an atmosphere layer and a globally averaged carbon cycle model. MAGICC evolved from a simple global average energy-balance equation, as with most other simple models.

While MAGICC is designed to provide maximum flexibility to match different types of responses seen in more sophisticated models, the approach in MAGICC's model development has always been to derive simple equations as much as possible from critical physical and biological processes. In other words, MAGICC is as simple as possible but as mechanistic as necessary. This process-based approach has a strong conceptual advantage in comparison to simple statistical fits that are more likely to quickly degrade in their skill when emulating scenarios outside the original calibration space of sophisticated models.

MANAGE

The Mitigation, Adaptation, and New Technologies Applied General Equilibrium (MANAGE) model is a recursive dynamic single-country computable general equilibrium (CGE) model designed to focus on energy, emissions, and climate change (Selva, 2019). In addition to the typical features, MANAGE includes a detailed energy specification that allows for capital/labour/energy substitution in production, intra-fuel energy substitution across all demand agents, and a multi-output multi-input production structure. MANAGE is a dynamic model that primarily employs the neo-classical growth specification, where labour growth is exogenous. Capital is accumulated as a result of savings/investment decisions. The model allows for a wide range of productivity assumptions, including autonomous efficiency improvements that can vary across agents and energy carriers. Also, the model has a vintage structure for capital that allows for putty/semi-putty assumptions with sluggish mobility of installed capital. This flexible model can be calibrated to Social Accounting Matrices (SAM). The latest version of the model incorporates recently developed price/volume splits of the energy sectors and CO_2 emissions. The model is implemented in the GAMS software, and an aggregation facility is used as a front-end to the model to allow for complete aggregation flexibility.

MEDEAS

Modelling Energy system Development under Environmental and Socioeconomic constraints (MEDEAS) is a set of policy-simulation dynamic-recursive models sharing the same conceptual modelling approach designed to apply system dynamics (Capellán-Pérez et al., 2020). Models have been developed at three different geographically aggregated scales of global (MEDEAS-W), European Union (MEDEAS-EU), and country-level for Austria, Bulgaria, and Spain (MEDEAS-AUT, MEDEAS-BGR, and MEDEAS-SP, respectively).

The MEDEAS models are structured in nine modules: economy, energy demand, energy availability, energy infrastructures and EROI, minerals, land use, water, climate/emissions, and social and environmental impact indicators. The biophysical limits associated with exploiting natural resources (energy and materials), the dynamic EROI, and the feedbacks between the modules play an essential role in the model.

MENA-EDS

The MENA-EDS is a large-scale energy model that simulates the formation of prices in energy markets, estimates the quantities demanded and supplied by the main energy system actors, and incorporates energy-related CO_2 emissions, environmentally oriented policy instruments, and emission abatement technologies (Fragkos et al., 2013). It is a recursive dynamic and partial equilibrium energy system model with annual resolution in which variables are either calculated directly or based on the previous years' values. The model is designed for medium- to long-term projections and generates quantitative analytical results in detailed energy balances for each country.

The model is currently being applied to the Southern Mediterranean countries and, more specifically to the region that contains Turkey, North Africa (Algeria, Libya, Egypt, Morocco, and Tunisia), and some Middle East countries (Syria, Lebanon, Israel, and Jordan). Final energy demand in the MENA-EDS model is simulated for three main sectors industrial, domestic/tertiary (including households, services, and agriculture), and transportation.

MUSE

The ModUlar energy system Simulation Environment (MUSE) is a modelling environment for assessing energy systems transitions over long time horizons, with a partial equilibrium on the energy system provided by iterative microeconomic supply-demand market clearing for each energy commodity (García Kerdan et al., 2019). Its scope is the entire energy system, from the production of primary resources such as oil or biomass, through the 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. The key distinguishing features of MUSE are modularity and its agent-based framework enabling of modelling of actual consumer, firm, and government investment and operational decision-making. Within the modular structure of the MUSE, each sector of the energy system is simulated by an individual module. This modular architecture of MUSE allows flexibility because each module can

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be run independently or linked with other modules via a market-clearing algorithm. As well as the modular separation of the energy sectors, the global energy system is also geographically disaggregated into regions, which can also be run independently. Hence, regional variations can be considered, including current technological stocks and socioeconomic advancements.

Under the MUSE framework, model implementations with various geographic scopes and objectives can be constructed. MUSE-Global is an application of a worldwide model in the MUSE framework that spans the years 2010 to 2100 and characterises 28 global areas. It has been used to demonstrate that somewhat sub-optimal transition pathways may be more likely to be successful than ideal ones and can be used to investigate several concerns on mitigation given realistic restrictions and frictions on system change.

PROMETHEUS

The PROMETHEUS is a global energy system model covering the complex interactions between energy demand, supply, and energy prices at the regional and global levels (Fragkos et al., 2015). PROMETHEUS is a fully-fledged global energy system model used to derive the evolution of the world energy system up to 2050 with annual time resolution. The PROMETHEUS is a partial equilibrium energy system model with a yearly recursive simulation process. PROMETHEUS has a modular structure with the most important modules, including macroeconomics, final energy demand, electricity production, energy prices, fossil fuel supply, and climate module. PROMETHEUS modules are linked to form a fully-fledged global energy system model and interact with each other through their standard variables and overall system constraints. The mathematical formulation of the model combines the top-down simulation of useful energy demand, based on econometrically estimated income and price elasticities, with the bottom-up representation of energy supply technologies.

PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (RES, electric vehicles, CCS, and energy efficiency) and policy instruments. The latter include market-based instruments such as cap and trade systems, sector-specific policies, and measures focusing on specific carbon-emitting activities. Key characteristics of the model include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements.

TIAM

The TIMES Integrate Assessment Model, TIAM, is the multi-region, global version of TIMES, which combines an energy system representation of fifteen different regions with options to mitigate non-CO_2 greenhouse gases as well as non-energy CO_2 mitigation options, such as afforestation in each of these regions (Anandarajah et al., 2013). Through a simple climate module, emissions from these sources are used to calculate temperature changes. As such, it can be used to explore various questions on how to mitigate climate change through energy systems and transformations, as well as reductions in non-energy CO_2 and non-CO_2 emissions.

Meanwhile, the TIMES framework is a modelling platform for local, national, or multi-regional energy systems, which provides a technology-rich basis for estimating how energy system operations will evolve over the long term. The energy system includes 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.

WILIAM

The WithIn limits Integrated Assessment Model (WILIAM), developed in the scope of the LOCOMOTION project, is a long-term model running at three global, European, and national geographical levels for the 27 EU member states and the United Kingdom (UK). It integrates various modules for water, land use, and society (including the endogenisation of the population). The economy module is developed to comprehensively represent production, consumption, government, international trade, finance, and climate change impacts, including the supply of materials.

The WILIAM model is built on the existing MEDEAS model developed in the context of the EU-funded MEDEAS project. For the study of the highly complex interactions between humans and their environment, the project draws on different techniques and methods, such as System Dynamics (SD) modelling, Input-Output Analysis (IOA), Energy Return On Investment (EROI) calculations, Life Cycle Analysis (LCA), land and carbon footprinting, microsimulation, and many others.

WTMBT

The World Trade Model with Bilateral Trades (WTMBT) is a meso-economic linear optimisation model based on the comparative advantage principle (Hammer Strømman et al., 2006). The model endogenously determines the production yields and trade patterns in each region concerning exogenously specified final demand. It minimises the use of factors of production (labour and capital) concerning the regional factors endowments (e.g., availability of natural resources, land, workforce, etc.).

The choice of developing a model which includes the cost of bilateral trades (i.e., WTMBT) is driven by the relevance of transport in determining the arrangement of production and trades and their non-negligible impact on carbon emissions. The economic and environmental implications of national and international transportation of products are included in the model and weighed depending on transport distances. Concerning General Equilibrium Models (CGE), the WTMBT requires less exogenous data since it considers household and government final demand as constant and perfectly rigid with respect to endogenous change in the prices of goods and services. Therefore, instead of maximising social utility, the highest-cost producers set the product prices, and each region chooses to produce or import by minimising the overall costs and complying with their own production factors availability (i.e., factor endowments). In the WTMBT, each country's production technologies, factor use coefficients, and final demand are derived from Multi-Regional Input-Output tables (MRIO).

3.1.2 The model documentation platform of I²AM PARIS

The I²AM PARIS is an open-access data exchange platform for modelling information in support of climate action. It was created in 2019 to facilitate understanding of the diverse Integrated Assessment Models (IAMs), energy system models, and sectoral models, as well as to provide interactive interfaces for intercomparisons of model results. The platform currently provides extensive documentation for more than 40 global, national, and sectoral models that are used to support climate policy analysis. Model details are provided through four diverse interfaces that offer relevant information for several use cases and different audiences. One of the interfaces is an interactive library of the models in a responsive infographic, which describes the models concerning their coverage, granularity, representation, and features. Figure 1 presents the TIAM model infographic extracted from the interactive library.

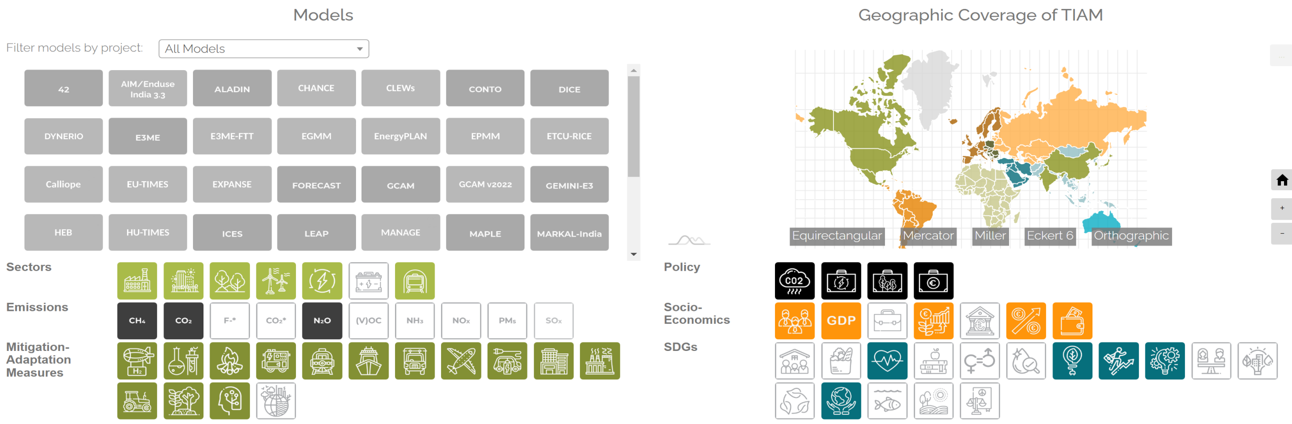

Figure 1. I²AM PARIS interactive library for TIAM model

The data behind the interactive library leads to a large model typology, documenting the coverage and capabilities of the models in various dimensions. The large tables, to be used for the mapping in the next section, can be found in the appendix. In the following pages, we thus instead present first data on the capabilities of models to capture specific policy instruments, developed for D4.1, and on a comparison of models across dimensions used for the models used in the latest IPCC report.

3.1.3 Policy representation in the models

The below tables first present a mapping of general mitigation/policy measures against our model portfolio, after which a similar exercise done for specific policy measures is shown. These tables are the output of T4.1 and are documented in (Noelia Ferreras et al., 2023). Y, P, and M in the tables show whether the policies could be represented, respectively, explicitly (Y), partially (P), or with modification (M). Blank cells indicate that the measure or instrument can't be represented in the model.

Table 6. Policy sectors and related types of measures represented in each model

POLICY SECTOR	SUBCATEGORY	POLICY MEASURES	CHANCE	IMACLIM-China	BLUES	GCAM	GCAM-USA	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	Calliope	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	DREEM (TEEM)	ATOM (TEEM)	WISEE-EDM Industry EU	WISEE-EDM Global Steel	WTMBT
BUILDINGS	Heating	Gas replacing oil / coal	Y			Y	Y	Y		Y	Y	Y	M	Y	Y	Y	Y		Y	Y	Y	Y				Y
		Biofuels				Y	Y	Y		Y	Y	Y	M	Y	Y	Y	Y		Y	Y	Y	Y				Y
		Electricity				Y	Y	Y		Y	Y	Y	M	Y	Y	Y	Y	M	Y	Y	Y	Y	Y			Y
		Hydrogen				Y	Y	Y		Y	Y		M	Y	Y	Y	Y		Y	Y	Y	Y				
		Solar thermal						Y		Y	Y		M	Y	Y	Y	Y			Y		Y				
		Building shell efficiency				M	P	M		M			M	Y	M		M		Y		Y	Y				
	Cooling	Electricity				Y	Y	Y	Y	Y	Y	Y	M	Y	Y	Y	Y	M	Y	Y	Y	Y				Y
		Building shell efficiency				M	P	M	M	M	M		M	Y	M		M		Y	M	Y	Y				Y
	Lighting	Efficient lighting	Y					Y	Y	Y	Y		M	Y	Y	Y	M		Y	Y	Y	Y				Y
	Appliances	Efficient appliances						Y	Y	Y	Y		M	Y	Y	Y	M		Y	Y	Y	Y				Y
INDUSTRY	Process heat	Gas replacing oil / coal	Y			Y	Y	M	Y	Y	Y	Y	M	Y	Y	Y	Y		Y	Y	Y			Y	Y (for steel only)	Y
		Biomass				Y	Y	M	Y	Y	Y	Y	M	Y	Y	Y	Y		Y	Y	Y			Y	Y (for steel only)	Y
		Hydrogen				Y	Y	M	M	Y	Y		M	Y	Y	Y	Y		Y	Y	Y			Y	Y (for steel only)	
		Electricity				Y	Y	M	Y	Y	Y	Y	M	Y	Y	Y	Y	M	Y	Y	Y			Y	Y (for steel only)	Y
	Machine drives	Gas replacing oil / coal	Y			Y	Y	M		Y	Y	Y	M	Y	Y	Y			Y	Y	Y					Y
		Electricity				Y	Y	M		Y	Y	Y	M	Y	Y	Y		M	Y	Y	Y			Y		Y
	Steam	Gas replacing oil / coal	Y			Y	Y	M		Y	Y		M	Y	Y	Y			Y	Y	Y			Y		
		Electricity				Y	Y	M		Y	Y		M	Y	Y	Y		M	Y	Y	Y			Y		
	CHP	Gas replacing oil / coal				Y	Y	M		Y	Y		M	Y	Y	Y	M		Y	Y	Y			Y		
		Biomass				Y	Y	M		Y	Y		M	Y	Y	Y	M		Y	Y	Y			Y		
	Overall industry	CCS		Y		Y	Y	Y	Y	Y	Y	Y			Y	Y	Y		Y	Y	Y			Y	Y (for steel only)	
		CDR/NETs					Y	Y	Y	Y						Y								M	M	
AGRICULTURE & LULUCF (Land Use, Land Use Change and Forestry)	Agric: Energy use	Gas replacing oil / coal	Y			Y	Y	Y	Y	Y	Y	Y	M	M	Y	Y	Y		Y	Y	Y					
		Biomass				Y	Y	Y	Y	Y	Y	Y	M	M	Y	Y	Y		Y	Y	Y					
		Electricity				Y	Y	Y	Y	Y	Y	Y	M	M	Y	Y	Y		Y	Y	Y					
	Agric: Land practices	Land yield maximisation				Y	Y	Y			Y			Y						Y						
		Organic fertilizer use									Y			M						Y						
		No tillage									Y			M						Y						
		Agroforestry									Y			Y						Y						
	Agric: Animal husbandry practices	Improved feeding practices				Y	P	Y			M									M						
		Manure management				Y	P	Y						M												
		Feed additives				M	P																			
	LULUCF	Afforestation				Y	Y	Y		Y	Y			Y						Y						
		Land protection				Y	Y				Y			Y						Y						
		Biomaterials				Y	Y																			
		Area set aside for nature (Biodiversity)				Y	Y				Y			M						Y						

Table 7. Policy sectors and related types of measures represented in each model (continued)

POLICY SECTOR	SUBCATEGORY	POLICY MEASURES	CHANCE	IMACLIM-China	BLUES	GCAM	GCAM-USA	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	Calliope	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	DREEM (TEEM)	ATOM (TEEM)	WISEE-EDM Industry EU	WISEE-EDM Global Steel	WTMBT
ENERGY	Synthetic fuel production	Coal to gas with CCS						Y		Y	Y	M		M	Y	Y			Y	Y	Y					M
		Coal to liquids with CCS				Y	Y	Y		Y	Y	M		M	Y	Y			Y	Y	Y					M
		Gas to liquids with CCS						Y		Y	Y	M		M	Y	Y	Y		Y	Y	Y					M
		Biomass to liquids				Y	Y	Y		Y	Y	M		M	Y	Y	Y		Y	Y	Y					M
		Biomass to liquids with CCS				Y	Y	Y		Y	Y	M		M	Y	Y	Y		Y	Y	Y					M
		Hydrogen to gas with CCU									Y						Y			Y						
		Hydrogen to liquid with CCU									Y						Y			Y						
	Hydrogen production	Electrolysis				Y	Y	Y		Y	Y			Y	Y	Y	Y	M	Y	Y	Y					
		Coal to hydrogen with CCS				Y	Y	Y		Y	Y				Y	Y			Y	Y	Y					
		Gas to hydrogen with CCS				Y	Y	Y		Y	Y			Y	Y	Y			Y	Y	Y					
		Biomass to hydrogen with CCS				Y	Y	Y		Y	Y				Y	Y	Y		Y	Y	Y					
	Electricity generation	Coal with CCS		Y		Y	Y	Y	Y	Y	Y	Y		M	Y	Y	Y	Y	Y	Y	Y					Y
		Gas with CCS		Y		Y	Y	Y	Y	Y	Y	Y		M	Y	Y	Y	Y	Y	Y	Y					Y
		Nuclear fission	M			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y
		Nuclear fusion						Y	Y	Y	Y				Y	Y				Y						
		Hydro	M	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y
		Biomass	M	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y
		Biomass with CCS		Y		Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y		Y	Y	Y					Y
		Geothermal	M			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y						Y
		Solar PV	M			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y			Y
		Solar CSP	M			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y					Y
		Onshore Wind	M			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y
		Offshore Wind	M			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y
	Heat generation	Coal with CCS		Y						Y	Y			Y	Y	Y	Y		Y	Y	Y					
		Gas with CCS		Y						Y	Y			Y	Y	Y	Y		Y	Y	Y					
		Oil with CCS		Y						Y	Y			Y	Y	Y	Y			Y						
		Geothermal								Y	Y		Y	Y	Y	Y	Y			Y						
		Biomass		Y		Y	Y	Y		Y	Y		Y	Y	Y	Y	Y		Y	Y	Y					
		Biomass with CCS		Y						Y	Y			Y	Y	Y	Y		Y	Y	Y					
TRANSPORT	Road	Gas (LNG / CNG) vehicles				Y	Y	Y	Y	Y	Y	M	Y	Y		Y	m			Y						M
		Hybrid electric vehicles				Y	Y	Y	Y	Y	Y	M	Y	Y		Y	m		Y	Y	Y					M
		Fully electric vehicles				Y	Y	Y	Y	Y	Y	M	Y	Y		Y	m	M	Y	Y	Y					M
		Hydrogen fuel cell vehicles				Y	Y	Y	Y	Y	Y	M		Y		Y	m		Y	Y	Y					M
		Biofuels in fuel mix				Y	Y	Y	Y	Y	Y	M	Y	M		Y	m		Y	Y	Y					M
		Efficiency	Y			M	Y	Y	Y	Y	Y	Y	Y	Y		Y	m		Y	Y	Y					Y
	Rail	Electric rail				Y	Y	Y	Y	Y	M	Y	Y	Y		Y	m	M	Y	M	Y					Y
		Hydrogen fuel cell rail				Y	Y	Y	Y		M			Y			m		Y	M						
		Efficiency	Y			M	P	Y	Y	Y	M	Y	M	Y		Y	m		Y	M						Y
	Aviation	Biofuels in fuel mix				Y	Y	Y	Y	Y	M		Y	M		Y	m		Y	M	Y					
		Hydrogen planes				Y	Y	Y	Y	Y	M			Y		Y	m		Y	M	Y					
		Electric planes				Y	Y	Y	Y	Y	M			Y			m		Y	M						
		Efficiency	Y			M	P		Y		M		M	Y		Y	m		Y	M	Y					
	Shipping	Gas (LNG / CNG)						Y	Y	Y	M		Y	Y		Y	m		Y	M	Y					
		Hydrogen				Y	Y	Y	Y	Y	M			Y		Y	m		Y	M	Y					
		Biofuels in fuel mix				Y	Y	Y	Y	Y	M		Y	M		Y	m		Y	M	Y					
		Electric				Y	Y		Y	Y	M		Y	Y		Y	m		Y	M						
		Efficiency	Y			M			Y		M		M	Y		Y	m		Y	M	Y					
Water	Water	Water management (efficient and saving)				M	Y				Y			Y						Y						
		Managing of floods/floods risk									M									M						
SOCIAL/BEHAVIOURAL	Behavioural/Consumption	Travelling less	Y			M	Y	M	M	M	M		M	Y					Y	M	Y					M
		Change mode of transport /occupancy	Y			M	Y	M	M	M	Y		M	Y		Y			Y	Y	Y					M
		Less energy service demand	Y	Y		M	Y	M	M	M	M		M	M		Y			Y	M	Y	Y				M
		Lower material consumption						M	M	M	M		M	M					Y	M	Y	P (M)				
		Less product demand	Y	Y		M	Y	M	M	M	M			M		Y			Y	M	Y	P (M)				
		Change of diet	M			M	Y	M			M			Y						M		P (M)				
		Less food waste				M	Y	M						Y								P (M)				M
		Change of values						M														P (M)	Y			
	Education	Climate education in schools																				P (M)	P (M)			
		Renewal of the contents and methodologies																								
		Disaster risk reduction																								
		Diet and Physical Activity												Y								P (M)				
		Health investment												M								P (M)				
	Labour	Minimum-wage policy											M	Y												Y
		Rural unemployment	M																							
		Urban unemployment	M																							
	Governance	Regulatory management system																								
		Quality of new regulations																								

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Table 8. Policy instruments represented in each model

POLICY INSTRUMENT	SUBCATEGORY OF POLICY INSTRUMENT	POLICY INSTRUMENT TYPE	CHANCE	IMACLIM-China	BLUES	GCAM	GCAM-USA	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	Calliope	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	DREEM (TEEM)	ATOM (TEEM)	WISEE-EDM Industry EU	WISEE-EDM Global Steel	WTMBT
Economic and financial instruments	Direct investment	Procurement rules																						P		
		RD&D funding																			Y	P (M)		P		
		Infrastructure investments	P			P	P				Y	Y	P	Y			P		P	Y	P	Y		P		Y
		Funds to sub-national governments					P															Y				
		Climate finance tools				P	P					P							P		P					P
	Fiscal incentives	FITs/FIPs	Y			Y	Y	P		P								Y	Y		Y	Y	Y			
		Energy taxes & Tax exemptions	Y	Y		Y	Y	P		P	P	Y		Y		Y	P	Y	Y	P	Y	Y	Y	P		Y
		Energy auctions																					Y			P
		Grants and subsidies	Y	Y		Y	Y	Y		Y	P	Y		Y	Y	Y		Y	Y	P	Y	Y	Y	P		Y
		Loans and soft loans				P	P							Y								Y	Y			
		User charges				P	P	P		P												Y	Y			
	Market-based instruments	GHG emissions allowance trading schemes	Y	Y		Y	Y	P		Y	Y					Y		Y	P	Y	Y	Y	P (M)			Y
		Green certificates				P	P	P		Y												P (M)	P (M)			
		White certificates				P	P	P														P (M)	P (M)			
		Carbon pricing	Y	Y		Y	Y	Y		Y	Y	P		Y	Y	Y	P	Y	Y	Y	Y	Y	P (M)	Y		Y
Regulatory instruments	Codes and Standards	Building codes				P	P												P		P	Y	P (M)			
		Industrial air pollution standards	Y			Y	Y	P			Y	Y								Y						Y
		Product standards				P		P		P		Y				Y										Y
		Sectorial standards	Y									Y				Y										Y
		Vehicle air pollution standards				Y	Y	P			Y								P	Y	P					
		Vehicle fuel-economy and emissions standards				Y	Y	Y		Y	Y		Y	Y		Y			P	Y	P					
	Targets, Quotas and Obligations	Renewable energy obligations	Y			Y	Y	P		P	Y	Y	Y	Y				Y	Y	Y	Y	Y	Y			Y
Soft instruments	Information and Education	Information provision																				P (M)				
		Performance Label (comparison or endorsement)																				Y				
		Professional training and qualificaiton																				P (M)				
		Advice or aid in implementation																				P (M)				
	Voluntary Approaches	Negotiated agreements (public-private sector)																								
		Public voluntary schemes																								
		Unilateral commitments (private sector)																	P		P					
Barrier removal		Grid access and priority for renewables											Y	Y	Y				P		P	P (M)				
		Net metering					P								P							Y	Y			
		Removal of fossil fuel subsidies	Y	Y		P	P			Y	Y	Y			Y	Y		Y	Y	Y	Y	Y		P		Y
		Removal of split incentives																				P (M)				
Policy support		Processes, plans and strategies																								
		Subnational and citizen participation																				P (M)				
		MRV																				Y				
		Institutional mandates																								
		International cooperation																								
		Institutional creation																								
Research & Development & Deployment		Demonstration project																				P (M)		Y		
		Research programme																			P	P (M)				

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3.1.4 Partial IPCC-style model comparison

The latest IPCC report has collected information about the models used for generating the pathways presented in the IPCC scenario database (IPCC, 2022). A subset of the information was also collected for the IAM COMPACT models when teams presented their models to other project partners. The following tables present this data, the attributes including regional scope, sectoral coverage, type of baseline or benchmark setup as a basis for mitigation policies comparison, technology diffusion, capital vintaging and sunsetting of technologies, and variety of discount rates approaches. Not all models provided the information and are thus missing from the table.

Table 9. Model comparison reflected in the latest IPCC report

	Type of model	Global integrated assessment, energy system, or sectoral models with focus on major emitters					Integrated assessment, energy, electricity, sectoral system models for national and subnational modelling analysis in regions of interest							Open-source modelling frameworks that have been implemented at the global and/or EU level, and/or will be used in national modelling as well as for building capacities in selected countries with limited such capabilities							
	Model name	GCAM	TIAM	MUSE	PROMETHEUS	WTMBT	EXPANSE	WISEE-EDM Industry EU	WISEE-EDM Global Steel	CHANCE	DyNERIO	GCAM-USA	MENA-EDS	MEDEAS	WILIAM	MANAGE	CLEWs	OSeMOSYS	Calliope	EnergyPLAN	DREEM & ATOM (TEEM suite)
	Partner	BC3	Imperial	Imperial	E3M	POLIMI	UNIGE	WI	WI	BC3	POLIMI	UMD	E3M	UVa, BC3, CARTIF	UVa, BC3, CARTIF	NTUA	KTH	KTH	POLIMI	AAU	UPRC
Characteristics of baseline/ benchmark setup	Well-functioning markets in equilibrium	X		X	X	X				X	X	X	X								
	Regulatory and/or pricing policies	X			X	X				X		X	X	X	X		x	x			X
	Socioeconomic costs & benefits of climate change impacts													X	X					X	
	Physical impacts of climate change on key processes	X					X					X		X	X		x	x	X	X	
Technology diffusion	Logit substitution	X			X		X					X	X	X	X				X		
	Constant elasticity of substitution				X					X			X								
	Lowest marginal cost w/ expansion constraint																				
	Technology choice depends on agents' preferences			X	X								X								X
	Technologies w/o constraints or marginal cost w/ expansion constraints			X	X	X							X							X	X
Capital vintaging and sunsetting of technologies	Single capital stock with fixed lifetime and load factor, early retirement via reduction in load																				
	Capital vintaging with fixed lifetime and load factors, early retirement of vintages or reduction in load	X	X	X	X			X	X			X	X								
	Single capital stock with fixed lifetime and load factor, without early retirement					X	X			X	X			X	X				X	X	
	Mix of the above for different technologies																				X
Discount rates	As a property of an intertemporal welfare function (social discount rate)																				
	In an objective function of an intertemporal optimisation, to sum values at different times	X				X					X	X					x	x			
	To compute lifecycle costs of investment decisions or ROI, in functions representing agents' investment chokes			X	X		X						X						X	X	X
Carbon dioxide removal	Direct air capture		X														x	x		X	
	Mineralisation of atmospheric CO2 through enhanced weathering of rocks														X						
	Afforestation / Reforestation													X	X		x	x		X	
	Restoration of wetlands																x	x			
	Biochar														X					X	
	Soil carbon enhancement, enhancing carbon sequestration in biota and soils														X						
	Ocean iron fertilisation																				
	Ocean alkalinisation																				
	Bioenergy with carbon capture and storage		X		X			X	X				X		X		x	x		X	
Employment market	Representation of involuntary employment									X				X	X						
	Wage clearing at equilibrium																				
	Endogenous representation of labour market									X				X	X						
	Perfect labour mobility across sectors									X				X	X						
Demand	Elasticity demand				X					X			X				x	x		X	
	In elasticity demand					X	X	X	X		X						x	x	X	X	
	Mix of the above																				X

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3.2 Policy questions, and model needs

The policy response mechanism has gone through the first cycle of scoping policy-relevant research questions from the policy steering groups, organised around four themes: European Industry, Electrification, Global Green Investment, and Behavioural Change (Conall Heussaff & Georg Zachmann, 2023). Note that there are additional steering groups organised for non-EU regions – these have not yet been met). For each of the themes, several stake holder meetings were held, and each meeting produced a set of preliminary research questions. The main elements of these were then summarised, and the initial research questions will next be further developed within the consortium, and in interactions with the core working groups, involving a broader set of stakeholders. The final research questions to be used in the modelling will be developed in this latter process.

As the research questions to be used for the modelling are not yet available, we illustrate our approach for matching questions with potential key model characteristics using a handful of the research questions that emerged during the sessions, each meant to reflect a specific takeaway conclusion in D2.2, drawn from the full body of sessions. The characteristics are investigated one by one, i.e. a given model may be able to provide information in one aspect required in the study, but would need to be linked with other tools to answer the research question. The purpose of this is the identify an initial list of possible model candidates, which, together with the interpretations of the research questions, would then be further discussed with the modelling teams during the model choice and linking process. The latter step, however, is not included, as the actual, final research questions are not yet available. Yet, this step will be crucial, as this process requires much interpretation for both requirements of the research question and how they map to model characteristics and is thus highly subjective.

In the remainder of this section, we will first introduce the research questions chosen to reflect the key takeaways, before analysing each of these in terms of model needs and mapping those needs against the information presented in Section 3.1. As noted above, this process is not meant to identify the final models to be used but develop preliminary inclusion and exclusion criteria that can define the set of models to be considered in the next stage.

3.2.1 Theme-specific takeaways and representative research questions

The information here is all taken from D2.2, with some minor modifications to some of the research questions.

Theme: European Industry

Takeaway: Policymakers are interested in the economic effects of different potential scenarios of European industrial organisations.

- *Research question:* What are the economic impacts of European industrial adjustment/relocation in response to higher energy costs, and how does this affect value chains in Europe and abroad?

Takeaway: The security of supply, cost-saving, and emissions impacts of reshoring vs. importing essential green technologies is of interest.

- *Research question:* What are the energy, climate, and labour implications of reshoring critical industries?

Takeaway: The potential for European hydrogen, specifically its possible production, demand, and cost in Europe, is a policy priority.

- *Research question:* What are the potential levels of hydrogen demand, available volumes, costs, and optimal usage in 2030 and 2040? How competitive is EU production against other hydrogen production regions, such as the Gulf of Mexico?

Theme: Electrification

Takeaway: The affordability dimension of increasing electrification will continue to be a central policy question.

- *Research question:* How will increasing electrification impact customers' bills?

Takeaway: Flexibility needs in future power systems are of vital importance and potentially underexplored.

- *Research question:* What are the flexibility needs for the future electricity system, and which options are best placed to provide it?

Takeaway: The optimal balance between grid investment on the one side and demand response, smart grids, and flexibility on the other is crucial to understand.

- *Research question:* To what extent are grids and storage complementary and how can local, distribution-level flexibility reduce the need for grid expansion?

Takeaway: Transition risk (e.g., supply chain disruptions of essential materials and products due to geopolitical instability) is a primary concern for policymakers regarding electrification.

- *Research question:* Are there supply-chain constraints on the potential ramp-up of clean technologies (Industrial capacity, rare earth materials, impacts on trade, geopolitical risks)? For which technologies more so than others?

Takeaway: Taking a holistic energy system perspective regarding electricity is becoming increasingly relevant.

- *Research question:* In what sectors/for which uses can hydrogen compete with electricity as an energy carrier?

Theme: Global Green Investment

Takeaway: Which regions are best suited for hydrogen production?

- *Research question:* Which manufacturing sectors are most likely to switch to hydrogen, and does the EU remain a competitive location for them?

Takeaway: Which countries and companies are likely to have direct access to critical raw materials and what are the implications for investment?

- *Research question:* How does the distribution of critical raw materials affect investment costs in Europe and around the globe?

Theme: Behavioural Change

Takeaway: Understanding the effects of heterogenous consumer preferences would complement research on behavioural change and could be implemented in the model suite.

- *Research question:* How does heterogenous risk aversion amongst consumers impact total system cost?

Takeaway: Providing estimates of which policies can drive behavioural change, in addition to the cost-saving and emission reductions of those changes, is of utmost interest to policymakers.

- *Research question:* Do certain policies have a greater impact on changing behaviour than others?

3.2.2 Analysis of research question-specific model needs

European Industry

What are the economic impacts of European industrial adjustment/relocation in response to higher energy costs, and how does this affect value chains in Europe and abroad?

The research question implies that both global and European regional scope is required in the modelling. Industrial competitiveness should be endogenously represented, as should the economic impacts following changes in competitiveness. Value chains should also be endogenously captured in the modelling so that the impacts on the chains are an output of the modelling (rather than input assumptions). In the question higher energy costs are implied, suggesting that this could be a scenario element, rather than a model outcome.

In terms of model typology dimensions, using the aggregated summary table drawn from the literature (see annex), the following dimensions (1st level) and elements (2nd level) in model capabilities are identified as potentially important for the research question:

- System coverage
    - Economy
- Analytic approach
    - General equilibrium
- Spatial coverage
    - Global, regional
- Economy & Financial
    - Physical/Financial outputs of firms
    - Traded (non-) energy goods

Looking at the tables on IAM COMPACT models in Sections 3.1.3, 3.1.4 and Annex I, MEDEAS and WILIAM cover macroeconomy, including the outputs of firms and trade of goods, and also have the required regional coverage. DyNERIO and WTMBT could also be suitable and should be included in the follow-up dialogue if this research question is also among the final ones.

What are the energy, climate, and labour implications of reshoring critical industries?

The model portfolio needs to be able to endogenously consider employment, and the factors affecting it. It further needs to have a detailed enough description of the industrial end-use sectors, so that energy and emission-related impacts can be endogenously considered. In terms of regional scope, the model should be able to distinguish the EU as a region.

Mapping the requirements to the typology leads to the following list:

- Systems coverage and interlinkages
    - Energy
    - Economy
- Spatial coverage
    - Regional (EU)
- Energy
    - Industry end-use (technologies)
- Social
    - Employment

As employment is tied to the broader economic situation, MEDEAS, WILIAM, DyNERIO and WTMBT could be considered, to cover this need. The first two of these models also capture endogenously employment, as do also EXPANSE, MENA-EDS, PROMETHEUS and TEEMSuite. Many models, also of the already mentioned, cover also the energy system and have the appropriate spatial coverage. Finally, a range of models includes industrial end-use technologies from the energy perspective (GCAM, TIAM, CLEWS, EnergyPLAN, WILIAM, CALLIOPE, CHINA-MAPLE, MENA-EDS, OSeMOSYS, PROMETHEUS, WISEE-EDM Industry EU), with MUSE, AIM-Enduse India, TIAM, CLEWS, DyNERIO, MEDEAS, WILIAM, China-MAPLE, MENA-EDS, OSeMOSYS, PROMETHEUS, WISEE-EDM Industry EU and WTMBT considering industry at a granular subsector level.

What are the potential levels of hydrogen demand, available volumes, costs, and optimal usage in 2030 and 2040? How competitive is EU production against other hydrogen production regions, such as the Gulf of Mexico?

The research question broadly aims to understand the role hydrogen could play in the wider energy system, so that the demand and supply of hydrogen are an endogenous result of the model, following from the competition against the alternative energy vectors and feedstocks. This also means that the supply, transmission and the various end uses of hydrogen should be captured at some level of detail. A model portfolio should have global coverage, with the EU as a distinguishable entity, so that the competition between the EU's own supply and imported hydrogen can also be endogenously captured.

As before, using the summary typology with the above analysis leads to the following list:

- Systems coverage and interlinkages
    - Energy
- Spatial coverage
    - Regional (EU)
    - Global
- Energy [for H_2]
    - Energy conversion (technologies)
    - Energy storage (technologies)
    - Energy grid (technologies)
    - Industry end-use (technologies)
    - Transportation end-use (technologies)
    - Buildings end-use (technologies)

Many models cover energy, and the EU, whereas the global models are GCAM, MUSE, TIAM, CLEWS, WILIAM, EnergyPLAN, OSeMOSYS, PROMETHEUS and WTMBT. The perhaps most central model characteristic for the question thus is the level of detail with which the hydrogen supply, transmission, storage and end-use technologies are captured. The data available for the IAM COMPACT tools provide more information than the summary typology, by for example listing the specific hydrogen production technologies available in a given model. In this preliminary, illustrative analysis we however limit ourselves to identifying whether a given model considered hydrogen technologies at all within a given sector. Considering the six hydrogen-related elements of the energy system above, no information is currently available about how the models capture the transmission of hydrogen ("Energy grid"). Beyond that, three models, EnergyPLAN, MENA-EDS and PROMETHEUS, model hydrogen in all the other five sectors listed. Further, three models, GCAM, MUSE and TIAM, cover four of the five, all omitting the use of hydrogen as an energy storage technology. CLEWS, WILIAM and OSeMOSYS cover three of the five, all of them omitting the buildings sector, with the other omitted sector varying across the models. A further six models consider hydrogen in at least one sector.

Electrification

How will increasing electrification impact customers' bills?

The question had been reinterpreted as "How will increasing electrification impact wholesale electricity prices"; the final bill to customers depends also on local circumstances, such as specific policies in place, but changes in wholesale prices can still be assumed to be the main driver in changes of consumer bills, especially when no additional assumptions are made about e.g. changes in policies or regulations. Also, only costs for electricity are considered, and other possible household costs indirectly related to electrification are not considered.

Required model characteristics

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Models would need to capture the effect of increased demand for electricity in selected sectors, depending on the scenario also possibly how much electricity consumption increases, and the feedback interactions between price changes and investment in generation and end-use technologies. Presumably, modelling the effects of different policy choices would also be part of the research activity.

The following model characteristics would probably be necessary or desirable in the models to be used (either individually or in sum for linked models):

1. Temporal resolution:
    a. Hourly (to simulate spot-market dynamics and prices, given a capacity mix; necessary for detailed modelling, but some models may be able to approximate electricity price dynamics without a full hourly simulation of electricity markets and dispatching)
    b. Seasonal (to model average electricity demand)
    c. Annual/multi-year (to simulate changes in generation capacity mix)
2. Spatial coverage: National (or potentially state/multi-state for countries with multiple electricity price regions)
3. Sectoral dynamics/energy:
    a. Electricity consumption in all end-use sectors (necessary to determine both wholesale price and capacity/transmission needs)
    b. Electricity generation technologies (necessary to determine supply and cost curves)
        i. Including electricity storage
    c. Electricity grid capacity (necessary to determine regional supply and price interlinkage between regions)
4. Evaluated policies:
    a. Cap and trade (to account for ETS costs for fossil generation)
    b. Fuel taxes (to account for national taxes)
    c. Feed-in tariff, capacity targets, and any other policies used by the EU or national governments to incentivise renewable generation deployment).
5. Represented markets (all needed to model wholesale electricity prices):
    a. Spot markets
    b. Balancing markets
    c. Capacity markets
    d. Future market (for electricity)
6. Evaluated GHGs and pollutants:
    a. CO_2 energy (from electricity generation, to account for ETS costs)

Models can probably still give useful results even if not everything under 4 and 5 are covered. The requirements for what policies and markets are supported will depend on exactly which scenarios are to be modelled.

<u>Candidate models</u>

To capture the full dynamics of electricity price evolution, a model would need to capture both electricity market dynamics and hour-by-hour dispatching of different generation technologies, as well as medium-/long-term investment and deployment of new generation and transmission capacity, as well as the interaction between the two. For even more comprehensive modelling, the interaction between electricity price, demand and investments in increased end-use efficiency should also be captured. It would probably also be highly desirable to be able to model the effect of different policies, targeted both at the power sector and end-use sectors, and run different policy scenarios.

Hardly any model would be able to capture all of this. But some energy system models that include both short-term power sector dynamics and longer-term technology deployment could probably capture a minimum of what is necessary as well as parts of the "nice-to-haves" mentioned above. Such models might include:

- EXPANSE
- DREEM and/or ATOM
- OSeMOSYS (?)

In addition, the following models reportedly do short-term, high-time-resolution simulations of the electricity system, and could be soft-linked to other models that capture the longer-term evolution of the capacity mix and end-use sector demand:

- EnegyPLAN
- Calliope

Higher-level models that don't model electricity market dynamics but do model energy sector dynamics and potentially could be good candidates for linking with the models above might include:

- GCAM
- MUSE
- TIAM
- CLEWs
- PROMETHEUS
- DyNERIO
- MENA-EDS
- MEDEAS/WILIAM

Which of the higher-level models above is appropriate would depend on what type of dynamics, what sectors and what policies are to be modelled in the relevant scenarios. It again also needs to be noted that the above model list is the first step, which would then need to be followed by a dialogue with the identified modelling teams.

What are the flexibility needs for the future electricity system, and which options are best placed to provide it?

Here "flexibility needs" is interpreted as meaning the ability of the electricity system to respond to and balance rapid changes in generation and demand, in particular, increases in variability of both generation and demand due to increasing renewable share in the power sector and electrification in end-use sectors.

What types of models are needed, will depend on how the "needs for the future electricity system" are defined. Below, it is assumed that the starting point is scenarios with a pre-determined evolution of electricity demand and deployment of electricity generation technologies and that the models would be used to investigate the effect of different choices of how to meet the resulting flexibility demand. Often demand and generation, however, are model outcomes, in which case one would also need models that simulate or optimise the future evolution of demand and generation based on some other starting point. If these models are not the same as the ones I arrive at below (i.e., they do not themselves model flexibility needs and flexibility solutions), they might need to be soft-linked to the models below.

<u>Required model characteristics</u>

To fully capture the effect of generation and demand variability, a model would need to represent electricity system dynamics with hourly resolution. To answer which options are "best" placed to provide flexibility, the model will also need to represent relevant technologies and solutions, including all relevant generation technologies, grid interconnectors and transmission capacities, as many storage options as possible (different types of battery storage, pumped hydro, etc. etc.), as well as demand-response mechanisms. It would ideally also need to represent hourly variations in wholesale electricity prices, and the effect of intra-day variability in prices on electricity demand (e.g., how demand would shift in response to large swings in prices resulting from shifts in the weather).

"Best" isn't clearly defined, but could mean a mix of price, reliability and fast or easy deployment. Depending on what definition is used, the models would need to include both prices for the different technologies (optionally evolving with a learning curve), technical parameters that relate to reliability, and/or be able to model bottlenecks in material supply and construction.

Relevant characteristics from the model typology:

1. Systems coverage and interlinkages:
    a. Energy
    b. Material (if trying to assess material supply and deployment bottlenecks for the relevant flexibility solutions)
2. Temporal resolution
    a. Hourly (to model generation/demand balance and flexibility needs)
    b. Seasonal or annual (to model deployment of flexibility solutions)
3. Spatial coverage
    a. National (or state/multi-state for countries with multiple balancing regions)
4. Energy
    a. Energy conversion
    b. Energy storage
    c. Energy grid
    d. Total end-use of electricity
5. Evaluated policies
    a. [Any policies to be included in the evaluation, see below]
6. Represented markets
    a. Spot markets
    b. Balancing markets
    c. Capacity market

As policy representation is not necessary to answer which options are "best", the above does not consider the types of policies the models would need to represent. If, however, the modelling should consider the effect of different policy choices on the flexibility needs or deployment of flexibility solutions, then either the effect of the relevant policies would have to be estimated outside of the model and imposed exogenously, or the models would need to be able to represent them endogenously.

"Evaluated GHGs and pollutants" have also not been listed, as emissions may not be relevant depending on the approach. However, if the scenarios include varying the generation mix, and/or if flexibility solutions with associated emissions are included, it may be necessary to include CO_2 from energy in order to include the cost effects of ETS. If health impacts are included in the assessment, then particulates and other pollutants would also need to be represented.

Candidate models

The following models appear both to have high time resolution and to represent relevant technologies:

- EXPANSE
- Calliope
- DREEM and/or ATOM
- EnergyPLAN

The following models do not have hourly time resolution, but could still be useful given their detailed representation of the energy system and storage technologies:

- CLEWs/OSeMOSYS
- WILIAM
- MENA-EDS

To what extent are grids and storage complementary and how can local, distribution-level flexibility reduce the need for grid expansion?

This is in practice a more specific version or subset of the previous question and the analysis of the question therefore ends with the same candidate models as for that question.

In addition to the requirements for the previous question, this question would additionally require the models to model electricity system dynamics at a very local level and distinguish household (rooftop) solar and battery storage from their grid-scale counterparts. The typology tables do not provide fine-grained enough information about whether any of the models (except maybe DREEM or ATOM) really do this, further underlining the need for the results of this step of the analysis to be taken to the modellers.

Are there supply-chain constraints on the potential ramp-up of clean technologies (Industrial capacity, rare earth materials, impacts on trade, geopolitical risks)? For which technologies more so than others?

This question covers the full system, as it relates to "clean technologies" more broadly, thus potentially touching every element of the broader integrated system. Limiting to <u>energy</u>, considering the theme under which the question emerged, would still require an <u>energy system</u>-wide coverage of the model portfolio. As trade, resources produced currently mainly outside the EU (rare earth <u>materials</u>) and geopolitical risks are also mentioned, <u>global coverage</u> is needed in the modelling. As the question focuses on the existence of constraints on the <u>technology ramp-up</u>, rather than assuming such constraints and assessing their impacts on the development, the modelling portfolio should ideally be able to describe (1) the industrial capacity for <u>producing</u> clean technologies, and limits to how quickly it can change, (2) the demand of rare earth materials for specific technologies, and the supply and market dynamics for the materials and (3) modelling technology-related <u>trade flows</u>. Geopolitical risks can, are in all likelihood best captured through scenarios.

The required model capabilities are rather specific and unusual for the type of analysis normally done. With this in mind, a general level mapping to the summary typology produces the following set of dimensions and elements:

- Systems coverage and interlinkages
    - Energy
    - Material
- Spatial coverage
    - Global
- Technology choice, diffusion, and sunsetting
    - [no explicit factor for capturing industrial capacity, but proxies for how constraints attached to it might affect diffusion. See below]
    - Logit substitution

    - Constant elasticity of substitution
    - Expansion and decline constraints
- Economic and financial
    - Physical/Financial outputs of firms
    - Traded (non-) energy goods

As before, energy is captured by most models, but only CLEWS, WILIAM, OSeMOSYS, DYNERIO and WISEE-EDM capture materials, at least to some extent. Whether this covers rare earth materials would need to be confirmed with the modelling teams. GCAM, MUSE, TIAM, CLEWS, WILIAM, EnergyPLAN, OSeMOSYS and PROMETHEUS fulfil the requirement about regional scope, whereas only MEDEAS and WILIAM provide information about the output of firms and non-energy trade. Finally, while the models do not generally endogenously model the drivers of the bottle necks, limits to technology diffusion on a more aggregated level are included at least for GCAM, PROMETHEUS, EXPANSE, GCAM-USA, MENA-EDS, MEDEAS, WILIAM, CALLIOPE (logit substitution) and PROMETHEUS (again), CHANCE and MENA-EDS (constant elasticity of substitution). These formulations can't answer *whether* supply constraints exist but can mimic their existence (to a certain extent).

In what sectors/for which uses can hydrogen compete with electricity as an energy carrier?

This is very similar to the European Industry question about hydrogen potential in the EU – the only difference is that here electricity is specifically noted as the competing option and no global modelling is necessary. This being the case, the focus is, as before, on the level of detail with which hydrogen is described in the energy system. The portfolio of models appropriate for this is the same to the industry question, with the exception of consideration for the global modelling scope.

Global Green Investment

Which manufacturing sectors are most likely to switch to hydrogen, and does the EU remain a competitive location for them?

A switch to hydrogen requires models with representation of hydrogen process heat, that is WISEE-EDM, Prometheus, OSeMOSYS, MENA-EDS, EnergyPLAN, China-MAPLE, CALLIOPE, WILIAM, MEDEAS, CLEWs, TIAM, AIM/EndUse-India, MUSE, GCAM and GCAM-USA (Those underlined can do it with modification). The research question also requires models with representation of hydrogen DRI, available at least in GCAM, TIAM and WISEE-EDM Industry and Global Steel. All of the above models have representation of industry sub-sectors (in all cases Iron & steel and Chemicals and in all cases Cement, except for MEDEAS and WILIAM).

The subset of the above models with EU-specific regions is WISEE-EDM, Prometheus, OSeMOSYS, MENA-EDS, EnergyPLAN, CALLIOPE, WILIAM, MEDEAS, CLEWs, TIAM, MUSE, GCAM, allowing one to compare EU as a location against the rest of the world. Analysis of EU industry competitiveness further requires representation of industry sectoral output and trade in a multi-region model (WTMBT).

How does the distribution of critical raw materials affect investment costs in Europe and around the globe?

Investment costs into a low-carbon future could be a sectoral or whole system question. Any model that represents one or more aspects of this is therefore potentially useful. Similarly, considering Europe and the globe means that any model could usefully address this question, at least partially. Critical raw material demand inputs into technologies and infrastructures require a model or database to track this material input, ideally over multiple regions including Europe (DyNERIO).

Behavioural Change

How does heterogenous risk aversion amongst consumers impact total system cost?

Equilibrium/optimisation models neglect agent heterogeneity, looking at an effective social planner that makes rational decisions to minimise total cost or maximise aggregate utility. Agent heterogeneity, including different preferences arising from risk perception, income stratification, and demographic or household characteristic, is important in the representation of consumer choices and affects consumption habits as well as the process of the diffusion of innovations, technologies, and practices (Mercure et al., 2016). Heterogeneity can be expressed as different household types, enabling to capture macroeconomic, distributional, and environmental asymmetry. Suitable models often introduce a behavioural individual risk aversion rate and a learning ability influencing the process of expectation formation (Biondo, 2018).

IAM COMPACT models possibly suitable for this analysis are WILIAM, CHANCE, IMACLIM-China and MEDEAS. They all represent income elasticities and private consumption endogenously. CHANCE and IMACLIM-China are General Equilibrium IAMs, while WILIAM and MEDEAS apply different techniques and methods, such as System Dynamics (SD) modelling, Input-Output Analysis (IOA), Energy Return On Investment (EROI) calculations, Life Cycle Analysis (LCA), land and carbon footprinting, microsimulation, and others. Note that none of the models, as such, necessarily consider risk and risk aversion as decision-making criteria, nor reflect the level of risk attached to specific decisions. Their general approach, however, may better allow integrating such characteristics to the model parametrisation than with other models.

MUSE, an agent-based model, could also be useful, as it can represent agents with imperfect foresight making decisions with limited knowledge (decisions under future uncertainties). It allows for different choices among agents based on, e.g., technology maturity, as some might consider technologies based on a certain market share.

Attitude towards risks and changes in consumer preferences can also be represented through heterogenous "hurdle rates" in a cost-optimisation model like TIAM. However, using such risk rates as proxies impacts technology pathways significantly and their selection is often criticised for lack of transparency (Keppo et al., 2021). What's more, heterogeneity among, not just across, representative agents can not be directly captured but requires further model modification (see e.g. (McCollum et al., 2018)).

Do certain policies have a greater impact on changing behaviour than others?

Governments often have comparatively little influence over individual choices, which introduces significant uncertainties in decarbonisation pathways that are related to consumer behaviour. Policies can have wide-ranging distributional impacts on households depending on their income and consumption patterns (Garcia-Muros et al., 2022). Tracing the impacts of policies and incentives on the adaptive behaviour of diverse consumers has so far been mostly overlooked in climate change mitigation modelling and environmental assessment research (Mercure et al., 2016).

Therefore, to answer this question, exploratory, and possibly empirical, analysis should capture key uncertainties in the energy system, including non-optimal actor behaviour. Identified "targeted" behaviours should be linked to influential factors/drivers of sustainable consumer behavioural change as well as to key barriers (Habib et al., 2021), and modelling should be able to convey whether objective behavioural change has occurred after implementing certain policies (Gifford et al., 2011).

Generally, ABMs can provide a more realistic representation of human behaviour and consumer preferences and can be used to examine for example if and how lifestyles change under certain policy mixes (Aksyonov et al., 2006). However, upscaling of ABMs for the assessment of economy-wide impacts and effects of national or EU policies is limited (Niamir et al., 2020).

Amongst the project model ensemble, policy acceptance can best be simulated in MUSE, which analyses the macro effects due to the underlying processes happening at the micro-level (Giarola et al., 2022). With that said, the model can reflect agent behaviour but doesn't include mechanisms that drive *changes* in that behaviour, if behaviour is understood as the broader value system that leads to specific actions, rather than the materialised actions themselves.

Agent heterogeneity could also be represented by introducing statistical distributions over agent perspectives that provide forecasting of the expected effectiveness of certain policies aimed at changing the behaviour of particular agents (e.g., consumer purchases, investment choices, land-use decisions) (Mercure et al., 2016). Logit and

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other types of discrete choice models are commonly used to represent choices in simulation models to endogenise heterogeneous information more directly within their solution frameworks (McCollum et al., 2017). There are also several studies using IAMs that incorporate some degree of consumer behaviour and policy impacts, including GCAM (for transport (Kyle & Kim, 2011)) and IMACLIM (for buildings (Giraudet et al., 2012)). Also here, however, the behaviour is an input to the models, rather than an output of it.

4 Strategy for model linking and integration

As previously noted, the formulation of the research questions is still in process, which in turn means that no final selections of models can yet be made – and no discussion of specific linking processes between the models can be investigated. This section will, therefore, focus on discussing the various, general elements that need to be considered in the model linking.

Model linking as a technical problem

As the review above pointed out, model linking often involves a number of problems that require compromises. The specific solutions to these depend on the specific models, and reaching a "perfect" linking process is often impossible, requiring careful consideration of the trade-offs to be made. In the following section, we will discuss a non-exhaustive list of problems that often appear in model linkages. Considering these already in the stage in which possible model combinations are discussed may help in the implementation of the links later.

Model linking often involves tools with different temporal and spatial scales. This may even be the aim of the exercise, to for example use a more temporally and spatially detailed model to assess the operation of the energy system optimised on more aggregated temporal and spatial scales. At the same time, it can very easily cause problems. For example, how should one downscale aggregated outputs to more detailed spatial and temporal scales? If these lead to infeasible systems, how does one communicate this back to the more aggregated model? How does one communicate back information about the aggregated system being suboptimal on the more granular level – as it almost certainly will be? Problems seemingly trivial, but in practise often laborious to solve, can very easily appear even when scales are the same, but e.g. regional aggregations are different. If a land use model aggregates all Nordic countries to a single region, but includes them in a broader North-Western region in another model, how does one exchange information between the two? All of the presented issues are solvable, but many solutions require a not insignificant amount of work and require a range of assumptions to be made beyond those already done for the two models.

Another area that requires attention is variable definitions. The to-be-linked models may include variables that are at least seemingly fully or partially overlapping. The similarly named variables may, however, reflect slightly or completely different real decision variables, e.g. due to different aggregation decisions. "Conventional coal power plant investments" may, for example, be an overarching category aggregating investments in most coal power plant types in one model, whereas it could refer to a subset of those types in another, or to a further coal power plant type not included at all in the aggregation in the first model. The specific variable definitions are at times difficult to find out and this can complicate the linking.

A partially connected issue is the system boundaries of the tools. For variable definitions, this means that a variable can be an endogenous decision variable, an exogenous input assumption, a background assumption driving other exogenous parameter value assumptions in the model or unconnected to the model. While variables/parameters unconnected to one tool can be ignored, and those that are exogenous to one and endogenous to another are what model linking usually focuses on, the other two cases can often present difficulties. The use of a variable in the background assumptions of another model may as well not be documented and, in case the specific variable drives a key assumption, can create inconsistencies if ignored. An example could be GDP as an exogenous, underlying driver of government-developed energy demand projections in one model, and an endogenous variable in another. Cases in which both models include the same variable as endogenous require one to decide which model(s) determine the value, and which model(s) use this value as fixed. If the overlaps between the models are large, e.g. a macroeconomic model includes within its modelled scope also all of the energy system, the overlaps can be large, even cover some models completely. This will either mean very complicated linking exercises, with a high number of contact points (Krook-Riekkola et al., 2017), or accepting compromises in terms of the consistency between the tools. Generally, the latter is always required, even if one aims at the former. Finally, the differing variable definitions noted above further complicate this.

Model foresight is also an element to be considered, also in connection to the extent of the full modelling horizon. A forward-looking, perfect foresight (optimisation) model produces a set of decisions for the full-time horizon, considering for each time step how the decisions made for a given time step affect those that come after it. A myopic, or recursive-dynamic, model makes decisions for a time period much shorter than the full time horizon, without consideration for what comes after the decision horizon. It then moves time forward, making the next step which is affected by the decisions done during the previous step, and reaches further into the future than it did. Linking two models with different approaches to foresight can create complexities, as the decision-making environment in the two models differs greatly. This also affects the interpretation of the results, as discussed below.

Models are most often linked in an iterative fashion so that they exchange data until the results stay, more or less, the same as in the previous iteration and the models have converged. The models often are large, however, and modelling teams exchange data manually, leading the iteration to omit any convergence considerations. The more models are involved, the more contact points (and therefore convergence criteria) they have, the more laborious the practical linking mechanisms are, and the more difficult it is to reach convergence between the tools.

If models share not variables, but exogenous assumptions, the scope of harmonisation needs to be determined. This may present challenges in terms of whether the definitions in the models for given parameters are fully consistent, as discussed above, but also creates practical problems due to the scope of data and assumptions included in large models. If the models have large overlaps, much of the data in them would need to be agreed upon and changed, which not only requires a significant amount of work but can also lead to model instability, as the models potentially enter untested parts of the solution spaces. Finally, harmonisation that would consider also, potentially important, background assumptions that drive specific parameter values in the model adds to the challenge. As with most challenges, also here the key would be to find the acceptable trade-offs and proceed accordingly.

Finally, the practical implementation of the data exchange between the tools can also present an obstacle. Quite often the linked models are run from various institutes, and in such cases, in absence of a specific platform built for it, practical reasons may force compromises on the linking set up that would not be made otherwise. Even with a dedicated, general platform and moving of data, implementing it in other tools, running the models and passing the data onwards can be a laborious exercise, especially when the portfolio of models is large, the contact points between the models are many and convergence across the models is sought. The technical implementation of the linking should not be separated from the more scientific planning, as trade-offs may well also need to be considered here.

Model linking as an epistemological problem

Single, stand-alone models have been typically designed to reflect a specific decision-making paradigm, through which the model results can then be interpreted. If, for example, a given model optimises a full energy system with perfect foresight, the model results describe what the best possible energy system might look like, if there was perfect knowledge about every element of the system from now to the end of the modelling horizon, and we measured "best" as suggested in the model formulation. This might drastically diverge from how the system *would* develop under the same technology assumptions: In reality, there are no agents with perfect foresight, there are more than just one agent (and the real world agents differ in their preferences), "best" in reality is typically measured differently from the model and so on. This being the case, the results of such a model do not even try to forecast how the system develops, but how it should be developed, if we agree with the basic assumptions of the model. Conversely, some tools are parametrised to historical data, so that their macro behaviour reflects what has been observed in reality, e.g. how the market share of a heating fuel changes as a function of its price, and the price of the other fuels. This model also has an internal logic, projecting the historical behaviour of the larger system into the future.

When different tools are linked to form a larger modelling portfolio, the internal rationale and consistency within the models are compromised, to expand the boundaries of the endogenously modelled system. The interpretation of the linked system is unlikely to coincide perfectly with any of the individual models and has to be thought through from the bottom up. Further complications to the interpretation are introduced through the trade-offs

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that were made due to technical reasons. For example, if harmonisation is not fully done and models individually still decide values for some explicitly or implicitly overlapping variables, the interpretation will be further complicated, It is thus of critical importance to think about the interpretation of the linked model portfolio already at the planning stage and see whether there would be flexibility to choose models that are, in their philosophy, more compatible than another combination would be.

In the next modelling cycle of this project, these guidelines will be further developed into a model-linking toolbox, to provide a workflow for model choice, linking and interpretation. The workflow will then be tested with the research questions and models chosen for the scenario modelling.

Annex I

The following tables present a comparison of models across different dimensions based on the data available on the I[2]AM PARIS platform (REP: Represented; ED: Endogenous; EXG: Exogenous; w MOD: with Modification).

Table AI.1. I[2]AM PARIS-based coverage and capabilities of the models regarding the sectors

Category/ Subcategory	Model Coverage																	
	CHANCE	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
Energy sources|Coal	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Energy sources|Lignite	Not REP	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Energy sources|Oil	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Energy sources|Natural Gas	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Energy sources|Nuclear	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Energy sources|Biomass	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Energy sources|Hydro	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Energy sources|Solar	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Energy sources|Wind	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Energy sources|Geothermal	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Energy sources|Tidal/ Wave	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
Energy sources|Other	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP
Energy sources|Aggregated	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP
Energy transformation|Electricity	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Energy transformation|Hydrogen	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy transformation|Oil refining	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Energy transformation|Gas-to-liquids	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy transformation|Coal-to-liquids	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy transformation|Coal-to-gas	Not REP	REP	REP	Not REP	Not REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy transformation|Bio-to-liquids	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy transformation|Bio-to-gas	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy transformation|Other	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Energy transformation|Aggregated	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Energy storage|Pumped-hydro	Not REP	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Energy storage|Batteries	Not REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP
Energy storage|Hydrogen	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP
Energy storage|Power-to-gas	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Energy storage|Other	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Energy storage|Aggregated	Not REP	REP	Not REP	Not REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Energy storage|Power-to-liquid	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP

Table AI.2. I[2]AM PARIS-based coverage and capabilities of the models regarding the sectors (continued)

Category/ Subcategory	Model Coverage																	
	CHANCE	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
Industry|Aggregated	Not REP	REP	Not REP	Not REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Agriculture	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
Industry|Cement	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Chemicals	Not REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Food processing	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP
Industry|Iron and steel	Not REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Non-ferrous metals	Not REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Other	Not REP	Not REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP
Industry|Pulp and Paper	Not REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Textiles and leather	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Transportation|Passenger|Airborne	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Passenger|Seaborne	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Passenger|Non-motorized	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Transportation|Passenger|Rail	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Passenger|Road	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Passenger|Aggregated	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
Transportation|Freight|Airborne	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Freight|Seaborne	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Freight|Rail	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Freight|Road	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Transportation|Freight|Aggregated	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
Buildings|Residential	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Commercial	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Public	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP
Buildings|Aggregated	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP
AFOLU|Crops	Not REP	REP	REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
AFOLU|Animals	Not REP	REP	REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
AFOLU|Bio-energy	Not REP	REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
AFOLU|Forestry	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
AFOLU|Aggregated	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP

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Table AI.3. I²AM PARIS-based coverage and capabilities of the models regarding the adaptation and mitigation

Category/ Subcategory	Model Coverage																	
	CHANCE	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
Adaptation|Additional cooling of buildings	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Building material choices	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Coastal protection	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Early warning systems	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Flood management	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Forest Fire management	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Green spaces in cities	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Land use adaptation/planning	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Retreat / Elevated infrastructure	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|River restoration/rehabilatation	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Adaptation|Water use restrictions	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Behavioural Changes|Travelling less	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Behavioural Changes|Less energy service demand	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP
Behavioural Changes|Lower material consumption	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Behavioural Changes|Less product demand	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Buildings|Heating|Gas replacing oil/ coal	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Heating|Biofuels	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Heating|Electricity	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Heating|Hydrogen	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Buildings|Heating|Solar thermal	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Heating|Building shell efficiency	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	REP	Not REP	Not REP
Buildings|Heating|Other	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP
Buildings|Lighting|Efficient lighting	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Appliances|Efficient appliances	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Cooling|Electricity	Not REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP
Buildings|Cooling|Building shell efficiency	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	REP	Not REP	Not REP
Industry|Process heat|Gas replacing oil/ coal	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Process heat|Biomass	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	REP	Not REP
Industry|Process heat|Hydrogen	Not REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Process heat|Electricity	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Machine drives|Gas replacing oil/ coal	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Industry|Machine drives|Electricity	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	REP
Industry|Steam|Gas replacing oil/ coal	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|Steam|Electricity	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	REP
Industry|CHP|Gas replacing oil/ coal	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	REP	Not REP
Industry|CHP|Biomass	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	REP	Not REP
Industry|Overall industry|CCS	Not REP	Not REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	REP	Not REP
Industry|Overall industry|CDR/NETs	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP

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Table AI.4. I²AM PARIS-based coverage and capabilities of the models regarding the adaptation and mitigation (continued)

Category/ Subcategory	Model Coverage																	
	CHANCE	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
Agriculture|Energy use|Gas replacing oil/ coal	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Agriculture|Energy use|Biomass	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Agriculture|Energy use|Electricity	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Agriculture|Land practices|Land yield maximisation	Not REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Agriculture|Land practices|Organic fertilizer use	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Agriculture|Land practices|No tillage	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Agriculture|Land practices|Agroforestry	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Agriculture|Animal husbandry practices|Improved feeding practices	Not REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Agriculture|Animal husbandry practices|Manure management	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Agriculture|Animal husbandry practices|Feed additives	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
LULUCF|Afforestation	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
LULUCF|Land protection	Not REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
LULUCF|Biomaterials	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Synthetic fuel production|Coal to gas with CCS	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Synthetic fuel production|Coal to liquids with CCS	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Synthetic fuel production|Gas to liquids with CCS	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Synthetic fuel production|Biomass to liquids	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Synthetic fuel production|Biomass to liquids with CCS	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Synthetic fuel production|Other	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Synthetic fuel production|Hydrogen to gas with CCU	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Synthetic fuel production|Hydrogen to liquid with CCU	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Hydrogen production|Electrolysis	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP
Hydrogen production|Coal to hydrogen with CCS	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Hydrogen production|Gas to hydrogen with CCS	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Hydrogen production|Biomass to hydrogen with CCS	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Hydrogen production|Other	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Electricity generation|Coal with CCS	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP
Electricity generation|Gas with CCS	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	Not REP
Electricity generation|Nuclear fission	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Electricity generation|Nuclear fusion	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Electricity generation|Hydro	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Electricity generation|Biomass	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Electricity generation|Biomass with CCS	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Electricity generation|Geothermal	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	Not REP	REP
Electricity generation|Solar PV	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Electricity generation|Solar CSP	Not REP	REP	REP	Not REP	Not REP	REP	REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	REP
Electricity generation|Onshore Wind	Not REP	REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP
Electricity generation|Offshore Wind	Not REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	REP	Not REP	REP

Table AI.5. I^{2}AM PARIS-based coverage and capabilities of the models regarding the adaptation and mitigation (continued)

Category/ Subcategory	Model Coverage																	
	CHANCE	**GCAM**	**MUSE**	**AIM/Enduse India**	**TIAM**	**CLEWs**	**DyNERIO**	**MEDEAS**	**WILIAM**	**China-MAPLE**	**EnergyPLAN**	**EXPANSE**	**MENA-EDS**	**OSeMOSYS**	**PROMETHEUS**	**TEEMSuite**	**WISEE-EDM**	**WTMBT**
Heat generation|Coal with CCS	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Heat generation|Gas with CCS	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Heat generation|Oil with CCS	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP
Heat generation|Geothermal	Not REP	Not REP	REP	Not REP	Not REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Heat generation|Biomass	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Heat generation|Biomass with CCS	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Road|Gas (LNG/ CNG) vehicles	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Road|Hybrid electric vehicles	Not REP	REP	REP	Not REP	REP	REP	Not REP	REP	REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Road|Fully electric vehicles	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Road|Hydrogen fuel cell vehicles	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Road|Biofuels in fuel mix	Not REP	REP	REP	Not REP	REP	REP	Not REP	Not REP	Not REP	REP	REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP
Road|Efficiency	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Road|Other	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Rail|Electric rail	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Rail|Hydrogen fuel cell rail	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Rail|Efficiency	Not REP	REP	REP	Not REP	REP	Not REP	REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP
Rail|Other	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Aviation|Biofuels in fuel mix	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Aviation|Hydrogen planes	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Aviation|Electric planes	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Aviation|Efficiency	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Aviation|Other	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Shipping|Gas (LNG/ CNG)	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Shipping|Hydrogen	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Shipping|Biofuels in fuel mix	Not REP	REP	REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Shipping|Electric	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Shipping|Efficiency	Not REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP	REP	REP	REP	Not REP	REP	Not REP	REP	Not REP	Not REP	Not REP
Shipping|Other	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Modal shifts|Replacing saturated means of transport	Not REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	REP	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	REP

Table AI.6. I²AM PARIS-based coverage and capabilities of the models regarding the socio-economic drivers

Category/ Subcategory	Model Coverage																	
	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MED REPEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-ED REPS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-ED REPM	WTMBT
Demography|Population	EXG REP	EXG REP	REP	EXG REP	EXG REP	EXG REP	EXG REP	EXG REP	EXG REP	Not REP	EXG REP	EXG REP	EXG REP	EXG REP	EXG REP	Not REP	EXG REP
Demography|Urbanisation	Not REP	EXG REP	REP	EXG REP	EXG REP	Not REP	Not REP	ED REP	EXG REP	Not REP	Not REP	Not REP	EXG REP	Not REP	EXG REP	Not REP	Not REP
GDP|GDP	EXG REP	EXG REP	REP	EXG REP	EXG REP	ED REP	ED REP	ED REP	EXG REP	Not REP	EXG REP	EXG REP	EXG REP	EXG REP	Not REP	EXG REP	ED REP
GDP|Private consumption	Not REP	Not REP	-	Not REP	EXG REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	EXG REP	EXG REP	EXG REP	ED REP	EXG REP	EXG REP
GDP|Public consumption	Not REP	Not REP	-	Not REP	EXG REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	EXG REP	Not REP	ED REP	EXG REP	EXG REP
GDP|Gross fixed capital formation	Not REP	Not REP	-	Not REP	Not REP	ED REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP
GDP|Exports	Not REP	Not REP	-	ED REP	Not REP	ED REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	EXG REP	ED REP
GDP|Imports	Not REP	Not REP	-	ED REP	Not REP	ED REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	EXG REP	ED REP
GDP|Trade balance	Not REP	Not REP	-	ED REP	Not REP	ED REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP
GDP|Aggregated	Not REP	Not REP	-	Not REP	Not REP	ED REP	ED REP	ED REP	Not REP	Not REP	Not REP	EXG REP	Not REP	EXG REP	Not REP	Not REP	ED REP
Employment|Total	EXG REP	Not REP	-	Not REP	EXG REP	EXG REP	ED REP	ED REP	Not REP	Not REP	ED REP	ED REP	EXG REP	ED REP	Not REP	Not REP	EXG REP
Employment|by eductional attainment level	Not REP	Not REP	-	Not REP	Not REP	EXG REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	EXG REP
Employment|by age	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP
Employment|by sex	Not REP	Not REP	-	Not REP	Not REP	EXG REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	EXG REP
Employment|by econcomic activity	Not REP	Not REP	-	Not REP	Not REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	ED REP	Not REP	ED REP	ED REP	Not REP	EXG REP
Employment|Aggregated	Not REP	Not REP	-	Not REP	Not REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	EXG REP
Investment|Macroeconomic	Not REP	Not REP	-	ED REP	Not REP	Not REP	ED REP	ED REP	Not REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Investment|Private Investments	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	EXG REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	ED REP	Not REP
Investment|Public investments	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	EXG REP	ED REP	Not REP	Not REP	Not REP	Not REP	ED REP	EXG REP	Not REP
Investment|Aggregated	Not REP	Not REP	REP	Not REP	ED REP	Not REP	ED REP	ED REP	Not REP	ED REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP
Public finances|Expenditures	Not REP	Not REP	-	Not REP	Not REP	Not REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP
Public finances|Receipts	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Public finances|Social benefits	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Public finances|Balances	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Public finances|Aggregated	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Economic activity|Production	ED REP	Not REP	REP	EXG REP	ED REP	EXG REP	ED REP	ED REP	Not REP	Not REP	ED REP	EXG REP	ED REP	EXG REP	Not REP	ED REP	EXG REP
Economic activity|Value added	Not REP	Not REP	-	EXG REP	Not REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	EXG REP	Not REP	EXG REP	ED REP	Not REP	EXG REP
Economic activity|Imports	ED REP	Not REP	-	ED REP	ED REP	EXG REP	ED REP	ED REP	Not REP	Not REP	ED REP	Not REP	ED REP	Not REP	Not REP	ED REP	EXG REP
Economic activity|Exports	ED REP	Not REP	-	ED REP	ED REP	EXG REP	ED REP	ED REP	Not REP	Not REP	ED REP	Not REP	ED REP	Not REP	Not REP	ED REP	EXG REP
Economic activity|Employment	Not REP	Not REP	-	Not REP	EXG REP	EXG REP	ED REP	ED REP	Not REP	Not REP	ED REP	ED REP	EXG REP	ED REP	ED REP	Not REP	EXG REP
Economic activity|Energy expenditure	ED REP	ED REP	-	ED REP	ED REP	EXG REP	ED REP	ED REP	Not REP	Not REP	ED REP	EXG REP	ED REP	EXG REP	ED REP	ED REP	EXG REP
Economic activity|Investments	Not REP	ED REP	-	ED REP	ED REP	Not REP	ED REP	ED REP	Not REP	EXG REP	ED REP	Not REP	ED REP	Not REP	ED REP	Not REP	Not REP
Economic activity|Raw material consumption	Not REP	Not REP	-	Not REP	ED REP	EXG REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	ED REP	EXG REP
Economic activity|Other materials consumption	Not REP	Not REP	-	Not REP	Not REP	EXG REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	EXG REP
Economic activity|Aggregated	Not REP	Not REP	-	Not REP	Not REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	EXG REP	Not REP	EXG REP	Not REP	Not REP	EXG REP
Incomes|Total gross/real disposable income	EXG REP	Not REP	-	EXG REP	Not REP	Not REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Incomes|Capital incomes	Not REP	Not REP	-	Not REP	Not REP	Not REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP
Incomes|Labour incomes	Not REP	Not REP	-	Not REP	Not REP	Not REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP
Incomes|Social transfers	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Incomes|By quantiles	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
Incomes|Energy poverty	Not REP	Not REP	-	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	EXG REP	Not REP	Not REP
Incomes|Aggregated	Not REP	Not REP	-	Not REP	Not REP	Not REP	ED REP	ED REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP

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Table AI.7. I²AM PARIS-based coverage and capabilities of the models regarding the emissions

Emission	Model Coverage																
	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
CO2	ED REP	ED REP	ED REP	ED REP	ED REP	EXG REP	ED REP	ED REP	ED REP	ED REP	ED REP	ED REP	ED REP	ED REP	ED REP	ED REP	EXG REP
CH4	ED REP	ED REP	-	ED REP	ED REP	EXG REP	ED REP	ED REP	Not REP	Not REP	Not REP	ED REP	ED REP	ED REP	Not REP	EXG REP	EXG REP
N2O	ED REP	ED REP	-	ED REP	ED REP	EXG REP	EXG REP	ED REP	Not REP	Not REP	Not REP	ED REP	ED REP	ED REP	Not REP	EXG REP	EXG REP
F-gases	ED REP	Not REP	-	Not REP	ED REP	EXG REP	EXG REP	EXG REP	Not REP	Not REP	Not REP	ED REP	ED REP	ED REP	Not REP	EXG REP	EXG REP
Land-use CO2	ED REP	EXG REP	-	Not REP	ED REP	EXG REP	EXG REP	ED REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	EXG REP
PMs (BC, OC, PM2.5)	ED REP	ED REP	-	Not REP	ED REP	EXG REP	Not REP	Not REP	ED REP	Not REP	ED REP	Not REP	ED REP	Not REP	Not REP	Not REP	EXG REP
SOx	ED REP	ED REP	-	Not REP	ED REP	EXG REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	EXG REP
NOx	ED REP	ED REP	-	Not REP	ED REP	EXG REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	EXG REP
NH3	ED REP	Not REP	-	Not REP	ED REP	EXG REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	EXG REP
CO / VOC	ED REP	Not REP	-	Not REP	ED REP	EXG REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	ED REP	Not REP	Not REP	Not REP	EXG REP

Table AI.8. I²AM PARIS-based coverage and capabilities of the models regarding the policies

Category/ Subcategory	Model Coverage																
	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
Emissions mitigation|Tax	REP	REP	REP	REP	REP	REP	REP w MOD	REP	REP	REP	REP	REP	REP	REP	REP	REP w MOD	REP
Emissions mitigation|Emissions target / quota (annual)	REP	REP	REP	REP	REP	Not REP	REP w MOD	REP	REP	-	REP	REP	REP	REP	REP w MOD	REP w MOD	REP
Emissions mitigation|Emissions target / quota (cumulative)	Not REP	REP w MOD	-	REP	REP	Not REP	REP w MOD	REP	REP w MOD	-	REP w MOD	REP	REP	REP	REP w MOD	REP w MOD	Not REP
Emissions mitigation|Regulations (emissions standards, etc...)	REP w MOD	Not REP	REP	REP	REP	Not REP	REP w MOD	REP	REP	-	REP w MOD	REP	REP w MOD	REP	Not REP	REP w MOD	Not REP
Emissions mitigation|Global Temperature/ Radiative Forcing target	REP	Not REP	-	REP	REP w MOD	Not REP	REP w MOD	REP w MOD	Not REP	-	Not REP	REP w MOD	Not REP	REP w MOD	Not REP	Not REP	Not REP
Emissions mitigation|Financial supports	Not REP	Not REP	REP	REP	REP	Not REP	Not REP	Not REP	Not REP	-	Not REP	REP w MOD	REP w MOD	REP w MOD	Not REP	REP w MOD	Not REP
Energy|Tax	REP	REP	REP	REP	REP	REP	REP w MOD	REP	REP	REP	REP	REP	REP	REP	REP	REP w MOD	REP
Energy|Subsidy	REP	REP	REP	REP	REP	REP	REP w MOD	REP	REP	-	REP	REP	REP	REP	REP	REP w MOD	REP
Energy|Energy mix target	REP	Not REP	REP	REP	REP	REP	REP w MOD	REP w MOD	REP	-	REP	REP w MOD	REP	REP w MOD	REP	REP w MOD	REP
Energy|Efficiency target	REP w MOD	Not REP	REP	REP	REP	REP	REP w MOD	REP w MOD	REP	-	REP w MOD	REP	REP w MOD	REP	REP	REP w MOD	REP
Energy|Regulations	Not REP	REP w MOD	REP	REP	Not REP	Not REP	Not REP	Not REP	REP	-	REP w MOD	REP	Not REP	REP	REP	REP w MOD	Not REP
Land|Protected lands	REP	Not REP	-	Not REP	REP	REP	REP w MOD	REP w MOD	Not REP	-	REP	Not REP	REP	Not REP	Not REP	Not REP	REP
Land|Production quotas	REP	Not REP	-	Not REP	REP	REP	REP w MOD	REP w MOD	Not REP	-	REP w MOD	Not REP	REP	Not REP	Not REP	Not REP	REP
Land|Carbon sink pricing / Land use change emissions tax	REP	Not REP	-	REP w MOD	REP	Not REP	REP w MOD	REP w MOD	Not REP	-	REP w MOD	Not REP	REP	Not REP	Not REP	Not REP	REP w MOD
Land|Afforestation targets	REP w MOD	Not REP	-	REP w MOD	REP	Not REP	REP w MOD	REP w MOD	Not REP	-	Not REP	Not REP	REP	Not REP	Not REP	Not REP	REP
Trade|Carbon border tax on imports	Not REP	Not REP	-	REP w MOD	REP	Not REP	Not REP	Not REP	Not REP	-	REP w MOD	REP w MOD	REP w MOD	REP w MOD	Not REP	Not REP	REP
Trade|Carbon border supports on exports	Not REP	Not REP	-	REP w MOD	REP	Not REP	Not REP	Not REP	Not REP	-	Not REP	REP w MOD	REP	REP w MOD	Not REP	Not REP	REP
Trade|Regulations policies	Not REP	Not REP	-	REP w MOD	Not REP	Not REP	Not REP	Not REP	Not REP	-	REP w MOD	REP w MOD	Not REP	REP w MOD	Not REP	Not REP	REP w MOD

Table AI.9. I²AM PARIS-based coverage and capabilities of the models regarding the SDGs

SDGs	Model Coverage																	
	CHANCE	GCAM	MUSE	AIM/Enduse India	TIAM	CLEWs	DyNERIO	MEDEAS	WILIAM	China-MAPLE	EnergyPLAN	EXPANSE	MENA-EDS	OSeMOSYS	PROMETHEUS	TEEMSuite	WISEE-EDM	WTMBT
§1. No Poverty	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
§2. Zero hunger	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP	(PART) REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP
§3. Health	Not REP	(PART) REP	Not REP	Not REP	(PART) REP	(PART) REP	(PART) REP	Not REP	(PART) REP	(PART) REP	Not REP	(PART) REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP
§4. Quality education	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
§5. Gender equality	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP
§6. Clean water and sanitation	Not REP	(PART) REP	Not REP	(PART) REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP
§7. Affordable and clean energy	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	(PART) REP
§8. Decent work & economic growth	Not REP	Not REP	Not REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	Not REP	(PART) REP
§9. Industry, innovation & infrastructure	Not REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	(PART) REP	(PART) REP	Not REP	(PART) REP	Not REP
§10: Reduced inequalities	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	(PART) REP	Not REP	Not REP	(PART) REP	(PART) REP	Not REP	(PART) REP	Not REP	Not REP	Not REP
§11: Sustainable Cities & Communities	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP
§12: Responsible production & consumption	Not REP	(PART) REP	Not REP	(PART) REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	Not REP	Not REP	Not REP	(PART) REP	Not REP	Not REP	(PART) REP	(PART) REP
§13: Climate action	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	(PART) REP	(PART) REP	(PART) REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP
§15: Life on land	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP	(PART) REP	(PART) REP	(PART) REP	Not REP	Not REP	(PART) REP	Not REP	(PART) REP	Not REP	Not REP	Not REP	(PART) REP
§16: Peace, Justice and institutions	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP	Not REP

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Annex II

A more aggregated summary typology reflecting the literature is presented below.

Table AII.1. Summary typology regarding approach and methodology

Systems coverage and interlinkages	Analytic approach	Methodology	Running technique	Mathematical formulation	Discounting method	Resource use	Technology choice, diffusion, and sunsetting
Energy	Top-down	Operation optimisation	Myopic	(Non) linear programming	Exogenous	Fixed price	Logit substitution
Economy	Bottom-up	Investment optimisation	Perfect foresight	Mixed-integer programming	Endogenous	Supply curve	Constant elasticity of substitution
Climate	Hybrid	Simulation	Stochastic	Fuzzy logic		Process model	Lowest marginal cost (w/o adjustment penalties)
Water	Partial equilibrium with price elastic demand	Accounting	Deterministic				Agent preferences
Land	Partial equilibrium with fixed demand	Econometric	Soft-linked				Expansion and decline constraints
Material (rather than energy)	General equilibrium	Economic equilibrium	Hard-linked				Learning curves
		System dynamics	Integrated				Intangible costs/benefits
		Agent based	Forecasting				Hurdle rates
			Exploring				Early retirement via reduction in load factor
			Backcasting				Early retirement via vintaging
							Disutility costs

Table AII.2. Summary typology regarding temporal and spatial granularity

Temporal resolution	Temporal horizon	Spatial coverage	Spatial resolution
Instantly	Short-term	Global	Number of nodes
Hourly	Mid-term	Regional	
Monthly	Long-term	National	
Seasonal	From a base year to a horizon year	State/Multi-state	
Annual		Local	
Multi-year			

Table AII.3. Summary typology regarding sectoral dynamics

Energy	Climatic	Land, forestry, and food	Economic and financial	Social
Energy utilization/extraction (technologies)	Atmosphere	Land Cover	Households	Population
Energy conversion (technologies)	Ocean	Crops	Financial firms	Population age structure
Energy storage (technologies)	Sea Ice	Animals	Non-Financial firms	Urbanisation
Eenrgy grid (technologies)	Land Surface	Bio-energy	Physical/Financial outputs of firms	Household Size
Industry end-use (technologies)	Biosphere	Forestry	Central Bank	Gender
Transportation end-use (technologies)	Ice Sheets		Government	Education
Buildings end-use (technologies)	Sediment and Weathering		Traded (non-) energy goods	Employment
Agriculture and forestry end-use (technologies)	Concentration (Exogenous/Endogenous)		Labor productivity	Income distribution
	Radiative Forcing (Exogenous/Endogenous)		Total factor productivity	
	GHG removal		Regional risk factors	

Table AII.4. Summary typology regarding accessibility

Integrated development environment	User interface	Training requirements	Users	Data availability	Data requirements	Licensing
GAMS + Solver	Graphical user interface	Low	Used by academics	No data	Qualitative	Open source
Vensim	Web-based user interface	Medium	Used by governments/public officials	Generalized open-source global data	Quantitative	Open-source upon request
Python	Direct coding and programming	High	Used by NGOs	Limited country-specific data	Monetary	Commercial
Windows with .NET	GUI with the possibility of coding if needed		Used by private/commercial users	Detailed open-source global data	Aggregated	Proprietary
MySQL			Very high number of users	Detailed country-specific datasets possibly in combination with global datasets	Disaggregated	Copyleft
R			High number of users			Permissive
Excel/VBA			Medium number of users			
Fortran			Low number of users			
GNU MathProg						
AMPL						
MATLAB						
AIMMS						
C++						
PHP						

Table AII.5. Summary typology regarding other dimensions

Evaluated policies	Reported cost measure	Represented markets	Evaluated SDGs/co-linkages	Evaluated GHGs and pollutants
Emission tax	Welfare loss	Spot markets	SDG 1 No poverty	CO2 energy
Emission pricing	Consumption loss	Balancing markets	SDG 2 Zero hunger	CO2 industrial processes
Cap and trade	GDP loss	Capacity market	SDG 3 Health	CO2 land-use change
Emission standards	Area under MAC	Future market	SDG 4 Quality education	CH4 fossil (combustion)
Fuel taxes	Equivalent Variation		SDG 5 Gender equality	CH4 fossil (fugitive and process)
Fuel subsidies	Energy System Cost Mark-Up		SDG 6 Clean water & sanitation	CH4 biogenic
Feed-in-tariff			SDG 7 Affordable & clean energy	N2O
Portfolio standard			SDG 8 Decent work & economic growth	HFCs
Capacity targets			SDG 9 Industry, innovation & infrastructure	PFCs
Energy efficiency standards			SDG 10 Reduced inequalities	SF6
Agricultural producer subsidies			SDG 11 Sustainable cities & communities	SO2
Agricultural consumer subsidies			SDG 12 Responsible production & consumption	Black carbon
Land protection			SDG 13 Climate action	Organic carbon
Pricing carbon stocks			SDG 14 Life below water	Non-methane volatile organic compounds
			SDG 15 Life on land	
			SDG 16 Peace, justice and institutions	

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