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D7.1 DOCUMENTATION OF GLOBAL IAMs

WP7 – Model Inter-Comparisons, Global Stocktake & Scientific Assessments

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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. Leadership of this task and deliverable was passed from Cambridge to NTUA.

2. Dissemination and uptake

This deliverable will serve as a reference document among consortium partners (experts and non-experts), as well as other researchers and members of the scientific (modelling and otherwise) community, to know about the available modelling capabilities, at the global level, within the PARIS REINFORCE consortium. It will also be used by policymakers and other stakeholder groups as a documentation of the modelling features of the PARIS REINFORCE global Integrated Assessment Models, serving as a means of facilitating their participation in the co-creation process envisaged in the project.

3. Short summary of results (<250 words)

This document presents the eight modelling tools to be used in WP7 of the PARIS REINFORCE research project. Its aim is to provide a good overview of each of the documented models for a large variety of stakeholders of climate policymaking at the global level. At the same time, it has sufficient technical detail so that experts can have an accurate overview of the provided documentation, and is organised in two parts: first, a summary and comparison of the main capabilities of the models; and, second, a section that documents each model individually, providing a more in-depth overview.

All eight models are global integrated assessment models, covering the world as one ore multiple regions, with some models featuring the capacity to also cover a multitude of specific countries. Although the models are significantly different from one another, they can be grouped into five categories: partial equilibrium (GCAM and TIAM), energy system (MUSE and 42), general equilibrium (GEMINI-E3 and ICES), optimal growth (DICE), and macroeconometric (E3ME) models.

The diversity of the models allows the consortium to consider a large set of mitigation measures in electricity and heat generation, buildings, transport, industry and to a lesser extent in agriculture. They cover a large set of technological options along with other features, such as behavioural changes. Furthermore, the models can deal with different policy instruments: emissions mitigation (e.g. cap-and-trade mechanisms), energy (e.g. efficiency and regulation), trade (carbon border taxation, green funds, etc.) and, by a smaller subset of these models, land policy instruments.

4. Evidence of accomplishment

This report.

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Preface

PARIS REINFORCE will develop a novel, demand-driven, IAM-oriented assessment framework for effectively supporting the design and assessment of climate policies in the European Union as well as in other major emitters and selected less emitting countries, in respect to the Paris Agreement. By engaging policymakers and scientists/modellers, PARIS REINFORCE will create the open-access and transparent data exchange platform I^{2}AM PARIS, in order to support the effective implementation of Nationally Determined Contributions, the preparation of future action pledges, the development of 2050 decarbonisation strategies, and the reinforcement of the 2023 Global Stocktake. Finally, PARIS REINFORCE will introduce innovative integrative processes, in which IAMs are further coupled with well-established methodological frameworks, in order to improve the robustness of modelling outcomes against different types of uncertainties.

NTUA - National Technical University of Athens	GR	
BC3 - Basque Centre for Climate Change	ES	
Bruegel - Bruegel AISBL	BE	
Cambridge - University of Cambridge	UK	
CICERO - Cicero Senter Klimaforskning Stiftelse	NO	
CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	IT	
E4SMA - Energy Engineering Economic Environment Systems Modeling and Analysis	IT	
EPFL - École polytechnique fédérale de Lausanne	CH	
Fraunhofer ISI - Fraunhofer Institute for Systems and Innovation Research	DE	
Grantham - Imperial College of Science Technology and Medicine - Grantham Institute	UK	
HOLISTIC - Holistic P.C.	GR	
IEECP - Institute for European Energy and Climate Policy Stichting	NL	
SEURECO - Société Européenne d'Economie SARL	FR	
CDS/UnB - Centre for Sustainable Development of the University of Brasilia	BR	
CUP - China University of Petroleum-Beijing	CN	
IEF-RAS - Institute of Economic Forecasting – Russian Academy of Sciences	RU	
IGES - Institute for Global Environmental Strategies	JP	
TERI - The Energy and Resources Institute	IN	

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Executive Summary

This document presents the eight modelling tools that will be used in WP7 of the PARIS REINFORCE research project. Its aim is to provide a good overview of each of the documented models for a large variety of stakeholders of climate policymaking at the global level. At the same time, it has sufficient technical detail so that experts can have an accurate overview of the provided documentation. For this purpose, the document is organised in two parts: first, a summary and comparison of the main capabilities of the models; and, second, a section that documents each model individually, providing a more in-depth overview.

All eight models are global integrated assessment models, covering the world as one ore multiple regions, with some models featuring the capacity to also cover a multitude of specific countries. Although the models are significantly different from one another, they can be grouped into five categories, following the classification found in the literature.

GCAM and TIAM are partial equilibrium models, in that they provide a detailed analysis of the interactions between environmental impacts and particular economic sectors, by trying to achieve market equilibrium separately in each and every sector of focus. In essence, they feature agents of the economy and of a detailed representation of the energy system, who indicate intended supply and/or demand for goods and services, and who are simulated so as to interact with one another so that supplies and demands are balanced in all markets and for every time step. In other words, market equilibrium is assumed to take place in each one of these markets (partial equilibrium) in the short-term.

MUSE and 42 are energy system models, and can therefore be considered as a subcategory of the partial equilibrium modelling group, providing a detailed account of the energy sector, i.e. energy technologies and their associated costs, in order to determine the least-cost ways of attaining GHG emission reductions or the costs of alternative climate policies. They both are bottom-up models that assume short-term microeconomic equilibrium on the energy system, which is achieved by iterating market clearance across all of the sector modules, interchanging price and quantity of each energy commodity in each region. MUSE, in addition, is also an agent-based model, as it tries to determine a mitigation pathway by providing an as realistic as possible description of the investment and operational decision making in each geographical region within a sector.

GEMINI-E3 and ICES are computable general equilibrium models, and therefore have a more detailed, multiple-sector representation of the economy and, rather than seeking optimal policies, they consider the impacts of specific policies on economic, social and environmental parameters. Their operation is similar to that of GCAM and TIAM, but differs in that market equilibrium is assumed to take place in the entire economy. Their richer representation of the economy comes at a cost in that the growth of the economy is harder to model and its structure more complex; as such, they require calibration to data on national and international socio-accounting information, as well as input in the form of a series of elasticities of substitution. Contrary to all other models, they also calculate economic indices endogenously.

Although DICE can also be considered as part of the general equilibrium family, it is distinguished as an optimal growth, or welfare optimisation, or neoclassical model, which does not feature the same level of sectoral or geographic detail (it exclusively covers the entire global economy). It determines the climate policy and investment levels that maximise welfare (future against present consumption) over time, by identifying the emission abatement levels for each time step; its social welfare function represents the world's well-defined set of preferences and accordingly ranks different consumption paths, with welfare increasing in per capita consumption for each generation but with diminishing marginal utility of consumption (the wealthier the world is, the less valuable an additional unit of consumption is).

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Finally, E3ME is a macroeconometric model. Quite like general equilibrium models, it is quite detailed in terms of energy technologies and geographic scope, but differs in that it does not assume that consumers and producers behave optimally or that markets clear and reach equilibrium in the short term. Instead, it uses historical data and econometrically estimated parameters and relations to dynamically and more realistically simulate the behaviour of the economy, by assuming that markets achieve equilibrium in the longer run.

The diversity of the modelling tools allows the consortium to consider a large set of mitigation measures in electricity and heat generation technologies, buildings, transport, industry and to a lesser extent in agriculture. They cover a large set of technological options along with other features, such as behavioural changes. Furthermore, the models can deal with different policy instruments: emissions mitigation policy instruments (e.g. taxation, cap-and-trade mechanisms and standards), energy policy instruments (e.g. taxation, efficiency and regulation), trade policy instruments (carbon border taxation, green funds, etc.) and, by a smaller subset of these models, land policy instruments.

The document at hand is the revised version (v1.10R) of deliverable D7.1. The deliverable has been revised with the aim of documenting a roadmap of the global model validation and evaluation steps to be followed in the project (Section 3).

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1 Introduction

The proliferation and growing variety of climate-economy models and what are known as integrated assessment models (IAMs) can make it difficult to place any specific model, or the discussion about the merits of one or another, into a broader context (Doukas and Nikas, 2020). In PARIS REINFORCE, about twenty modelling frameworks are expected to be used for national, regional and global climate policy and decarbonisation analyses. In order to better organise this rich modelling ensemble, the analyses and respective models have been sorted geographically and broken down into three work packages (WPs). These are **WP5**, including regional-level analysis for the European Union (EU), as an aggregated region, and national-level analysis for European countries within and outside the EU region; **WP6**, including national-level analysis for major emitting economies and less developed/emitting countries outside Europe; and **WP7**, including the global-level analyses and subsequent model inter-comparisons, with a focus on enhancing the deployment of IAMs in performing global analyses of the Paris Agreement and on contributing to the effective design of the global stocktake as well as to scientific assessments of possibilities of enhancing the ambition of NDCs and establishing mid-century strategies.

This document is intended to be a relatively simple (non-technical) and accessible description of WP7 (global) models that can be understood by non-expert stakeholders. Table 1 provides the main features of these eight models.

- **GCAM** is a global, partial equilibrium IAM that represents both human and Earth system dynamics, and explores the behaviour and interactions between the energy system, agriculture and land use, the economy and climate, towards mapping the implications of uncertainty in key input assumptions and parameters into implied distributions of outputs, such as GHG emissions, energy use, energy prices, and trade patterns.
- **TIAM** is a multi-region, global version of TIMES, an energy system modelling platform with a technology-rich basis for estimating how energy system operations will evolve over a long-term time horizon; as a global, partial equilibrium model that combines an energy system representation of fifteen different regions with mitigation options, it can be used to explore a variety of questions on how to mitigate climate change through energy system and transformations.
- **MUSE** is a modelling environment for the assessment of how national or multi-regional energy systems might change over time, covering the entire energy system; it is both a partial equilibrium and an agent-based model, in that it provides a detailed account of the energy sector, while developing an accurate description of investment and operational decision making.
- **42** is a simulation model for estimating CO_2 emissions associated with energy consumption in the world, which is divided into 50 countries/regions, aimed at describing in detail the target characteristics of the energy sector of each of these countries/regions for their effective integration into the global process of regulating emissions; as well as at calculating the impacts of possible structural changes and improvements in energy use efficiency.
- **GEMINI-E3** is a multi-country, multi-sector, recursive general equilibrium model that simulates all relevant markets as perfectly competitive, in order to calculate inter alia carbon taxes, marginal abatement costs and prices of tradable permits, abated emissions, welfare loss and components, macro-economic indicators, exchange rates and interest rates, and data at the industrial level.
- **ICES** is a recursive-dynamic, multi-regional general equilibrium model developed to assess impacts of climate change on the economic system and to study mitigation and adaptation policies, while allowing

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for the analysis of market flows within a single economy and international flows with the rest of the world; the model is linked to a post-processing module focusing on all Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development.

- **DICE** is a global, optimal growth or welfare optimisation IAM that represents the economic, policy and scientific aspects of climate change, integrating the climate system in the framework of economic growth theory.
- **E3ME** is a global macroeconometric (input-output) model that can be used to explore sectoral impacts, delve into socioeconomic dimensions, and look into the distributional and gender implications of nationally determined contributions (NDCs), mid-century strategies and Paris Agreement goals.

The diversity in terms of focus, scope and capabilities of these eight models allow the consortium to tackle a large range of questions related to global climate action. In the first part of this document, we examine more precisely the technologies and policies that this set of models can incorporate and/or assess, comparing their structure and properties, searching for “leads” allowing their combination into a more powerful assessment framework. The second part documents each model separately so that expert readers are able to understand their structure, components and geographic, sectoral, emissions and socioeconomic coverage.

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		GCAM	TIAM	MUSE	42	GEMINI-E3	ICES	DICE	E3ME
Full name		Global Change Assessment Model	TIMES Integrated Assessment Model	ModUlar energy system Simulation Environment	42	General Equilibrium Model of International-National Interactions between Economy, Energy and the Environment	Intertemporal Computable Equilibrium System	Dynamic Integrated model of Climate and the Economy	Energy-Environment-Economy Macro-Econometric Model
Type of model		Partial Equilibrium	Partial Equilibrium	Part. Equilibrium; Energy System; Agent-based	Energy System	General Equilibrium	General Equilibrium	Welfare optimisation	Macro-Econometric
Reference paper(s)		Edmonds et al. (1994)	Loulou and Labriet (2008)	Sachs et al. (2019a)	Uzyakov et al. (2016)	Bernard and Vielle (2008)	Eboli et al. (2010)	Nordhaus (1992)	Barker (1998)
Team running the model		BC3	Grantham, E4SMA	Grantham	IEF-RAS	EPFL	CMCC	BC3	Cambridge
Time horizon (final simulation year)		2100	2100	2100	2045	2050	2050	2300	2050 (2100)
Time steps in solution (years)		5	10	10	1	1	1	5	1
Sectoral granularity	**Macro-economic**	Exogenous	Exogenous	Exogenous	Exogenous	Detailed	Detailed	Yes (GDP)	Detailed
	Agriculture	Detailed	Yes	Yes	Yes	Yes	Yes	No	Yes
	Energy supply	Detailed	Very detailed	Detailed	Very detailed	Yes	Yes	No	Detailed
	Industry	Yes	Very detailed	Detailed	No	Aggregated	Aggregated	No	Yes
	Transport	Detailed	Very detailed	Detailed	Very detailed	Detailed	Aggregated	No	Detailed
	Buildings	Yes	Very detailed	Detailed	Detailed	Aggregated	Aggregated	No	Yes
	Land use	Very detailed	Limited	Yes (bioenergy)	Yes (bioenergy)	No	Yes	No	Yes

Table 1: Details of global models to be used in the project

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2 What can this range of models explore?

The diversity of the PARIS REINFORCE project's entire modelling ensemble is an asset and, in order to make efficient use of the available models, we must inform on their potential uses for climate policy support. Evidently, not all questions can be equally addressed by all models, nor will all models that can address a specific question give similar answers. The policy issues to be addressed by the models are mainly related to mitigation of and adaptation to climate change, although all eight models are better suited for studying mitigation options than they are for delving into adaptation; as well as to overall sustainable development.

This section begins with the presentation of the main drivers, or exogenous variables, such as socioeconomic assumptions, that are considered essential inputs for the modelling simulations. Once defined, the mechanisms involved in each model in the climate action scenarios are defined. After considering these drivers and mechanisms, we take stock of policy instruments that can be implemented in each model either directly or after specific modelling adjustments. Finally, we provide a short overview of how a transition pathway is calculated as well as of example use cases for each model. A detailed account of the information included in this section is presented in the documentation of Section 3.

2.1 Socioeconomic assumptions

Before exploring the capabilities of the eight models, we first present here the main drivers and exogenous assumptions necessary for the modelling simulations. This includes GDP and population growth on the one hand, which are the core socioeconomic pillars of integrated assessment modelling input and usually based on universal socioeconomic databases like the Shared Socioeconomic Pathways (SSP) framework (Riahi et al., 2017), and other key parameters on the other, which largely vary among the models.

Regarding the former, all eight models require inputs on population projections. This is the case for GDP growth, with the exception of the general equilibrium models (DICE, as an optimal growth model, included), which essentially require GDP data for calibration but then endogenously calculate GDP along with other macroeconomic indicators, such as consumption, trade, employment, investments and public finance indices.

As far as other key parameters are concerned, these vary greatly by model, mainly due to their mathematical and economic structure. For example, computable general equilibrium models like GEMINI-E3 and ICES require detailed information on national and international social accounting matrices, government transactions and other flows, which are used for calibrating the models and usually draw from specific databases. But what all models have in common, beside specific socioeconomic assumptions, are data requirements for technological specifications, in energy markets, electricity generation mixes and, where applicable, vehicle fleet size and structure.

Main socioeconomic assumptions and key parameters for all eight models are presented in Table 2.

Table 2: Details of socioeconomic assumptions and other key parameters

Model	Population growth	Economic growth	Other key parameters
GCAM	Exogenous	Exogenous	Labour participation and productivity; energy technology costs, performance, water requirements; agricultural technology crop yields, costs, carbon contents, water requirements, fertiliser requirements; resources (fossil fuels, wind, solar, uranium and

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			groundwater); and policies (emissions constraints, renewable portfolio standards, etc.).
TIAM	Exogenous	Exogenous	Fossil fuel availability and cost (i.e. supply curves); technology availability and costs; information about under construction/planned/possible energy technologies; regional emissions reduction goals; and energy efficiency improvements rates.
MUSE	Exogenous	Exogenous	Degree to which energy demand and demand for other goods and services resulting in GHG emissions change over the time horizon (future demand projections of each service in each region are based on population and GDP growth).
42	Exogenous	Exogenous	Vehicle fleet and structure; structure of electricity and heat production; sectoral energy intensities; fuel efficiency for cars and trucks; and fuel efficiency for electricity and heat plants.
GEMINI-E3	Exogenous	Endogenous (exogenous for calibration)	Energy markets in physical units; detailed social accounting matrices; indirect taxation; and government expenditures (for calibration).
ICES	Exogenous	Endogenous (exogenous for calibration)	National social accounting matrices; economic flows related to fuel-specific energy production and consumption; international sectoral statistics; international transactions among governments and transactions/flows between government and private households, and public debt (for calibration).
DICE	Exogenous	Endogenous	Overall savings rate for physical capital and rate of control of GHG emissions.
E3ME	Exogenous	Endogenous (exogenous for calibration)	

2.2 Mitigation and adaptation measures included in each model

This section presents the different mitigation and adaptation options included in the eight models, as detailed in Tables 3 to 6.

Upstream technologies like hydrogen production and synthetic fuel production are covered in detail as mitigation options in MUSE, which covers almost all existing technologies. GCAM and TIAM only include coal and biomass to liquids production, with and without carbon capture and storage/sequestration (CCS); but, like MUSE, both models include most hydrogen production technologies. GCAM however additionally features thermal splitting but not biomass to hydrogen (with CCS). It should be noted that E3ME also includes a limited number of upstream technologies but not to the same detail as the other three models.

With the exception of DICE, all models cover a large set of mitigation options in the electricity generation sectors, ranging from nuclear to renewables: CCS, hydro, solar photovoltaic (PV) and concentrating solar power (CSP), onshore and offshore wind turbines, biomass (with and without CCS) and geothermal; the general equilibrium

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models (GEMINI-E3 and ICES), however, feature less technological detail, while contrary to most other models 42 also includes nuclear fusion (along with TIAM) and do not distinguish onshore and offshore wind. Regarding heat generation, only 42, MUSE and TIAM feature significant detail, while GCAM includes heat from biomass.

In the building sector, the energy system (42 and MUSE) and partial equilibrium (GCAM and TIAM) models include mitigation options to lesser or larger extent; while GEMINI-E3 includes building technologies as an aggregated parameter; and ICES only covers behavioural changes and electricity for cooling as exogenous shifts in households' energy demand.

In the transport sector, GCAM, TIAM, MUSE and 42 again cover all or almost all technologies for road transportation, while GEMINI-E3 only includes fully electric vehicles. The technological options for GHG emission reductions in aviation and shipping are relatively limited, and only in the four abovementioned models, covering biofuels (GCAM, TIAM, MUSE, 42), hydrogen (TIAM), electricity (MUSE) and efficiency (TIAM, 42) in aviation; and gas (MUSE, 42), hydrogen (TIAM, MUSE), biofuel (all four) and efficiency (42) in shipping. Railways electrification is also available in all four models (and GEMINI-E3), while MUSE also includes hydrogen fuel cell rail. Finally, modal shift can be used to favour low-carbon transports in GCAM and GEMINI-E3, which two along with ICES also include behavioural changes in the transport sector.

For the manufacturing sectors, GCAM, TIAM, MUSE and 42 include various mitigation options for heat processing, machine drives, steam, combined heat and power (CHP); while GEMINI-E3 covers some of them as an aggregate. In addition, MUSE also includes CCS options in industry, as is the case for TIAM as well, which however also includes direct air capture (DAC).

To mitigate GHG emissions from agriculture, MUSE, 42, TIAM and GEMINI-E3 cover energy use in detail, whereas GCAM includes mitigation options for land yield maximisation and improved feeding. GCAM, GEMINI-E3 and ICES also cover behavioural change mitigation options, such as reductions in demand.

In land use, land-use change and forestry, the available mitigation options in the modelling ensemble are afforestation (GCAM, TIAM and MUSE), land protection (GCAM and MUSE) and biomaterials (GCAM).

The models documented in this deliverable do not in general produce outputs that are directly relevant to adaptation considerations but can offer indirect insights to inform adaptation planning. The GCAM model has some consideration of adaptation, directly allowing the set-aside of protected land, as well as directly calculating the additional cooling requirement of buildings as the climate warms, while ICES covers restrictions to water use.

In principle, adaptation measures could be included as a consideration in all models' simulations of mitigation pathways, through for example limiting bioenergy resources (e.g. to represent adaptation to crop yield reductions in a warming climate), or increasing building cooling requirements exogenously given the expectation of a warmer climate. However, these models do not project the impacts of a changing climate, so they are of limited use for adaptation considerations.

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Table 3: Mitigation options in each model for upstream technologies, electricity and heat generation technologies and buildings

				GCAM	TIAM	MUSE	42	GEMINI-E3	ICES	DICE	E3ME
Mitigation measures	Upstream technologies	*Synthetic fuel production*		✓	✓	✓					✓
		Hydrogen production		✓	✓	✓					✓
	Electricity and heat generation technologies	*Electricity generation*	CCS	✓	✓	✓	✓	✓			✓
			Nuclear fission	✓	✓	✓	✓	✓			✓
			Nuclear fusion		✓		✓				
			Hydro	✓	✓	✓	✓	✓	✓		✓
			Biomass	✓	✓	✓	✓				✓
			Biomass with CCS	✓	✓	✓					✓
			Geothermal	✓	✓	✓	✓				✓
			Solar PV & CSP	✓	✓	✓	✓	✓	✓		✓
			Wind onshore & offshore	✓	✓	✓	✓	✓	✓		✓
		Heat generation	CCS			✓	✓				
			Geothermal			✓	✓				
			Biomass	✓	✓	✓	✓				
	Buildings	*Heating*	Gas replacing oil / coal	✓	✓	✓	✓	✓*			
			Biofuels	✓	✓	✓	✓				
			Electricity	✓	✓	✓	✓	✓*			
			Hydrogen		✓	✓	✓				
			Solar thermal		✓	✓	✓				
			Building shell efficiency				✓	✓*			
		Lighting	Efficient lighting		✓	✓		✓*			
		Appliances	Efficient appliances		✓	✓		✓*			
		Cooling	Electricity	✓	✓	✓			✓		
		Behaviour change (less energy service demand)		✓					✓		

*: Aggregated parameters for GEMINI-E3 model

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Table 4: Mitigation options in each model for transport

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

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Table 5: Mitigation options in each model for industry and agriculture

				GCAM	TIAM	MUSE	42	GEMINI-E3	ICES	DICE	E3ME
Mitigation measures	Industry	*Process heat*	Gas replacing oil / coal	✓	✓	✓	✓	✓*			
			Biomass	✓	✓	✓	✓				
			Hydrogen	✓	✓	✓					
			Electricity	✓	✓	✓	✓	✓*			
		Machine drives	Gas replacing oil / coal		✓	✓	✓	✓*			
			Electricity		✓	✓	✓	✓*			
		Steam	Gas replacing oil / coal		✓	✓		✓*			
			Electricity		✓	✓		✓*			
		CHP	Gas replacing oil / coal	✓	✓		✓	✓*			
			Biomass	✓	✓	✓	✓	✓*			
		Overall industry	CCS		✓	✓					
		Behaviour changes (lower mat. consumption)						✓	✓		
	Agriculture & LULUCF	*Energy use*	Gas replacing oil / coal		✓	✓	✓	✓			
			Biomass		✓	✓	✓				
			Electricity		✓	✓	✓	✓			
		Land practices	*Land yield maximisation*	✓							
		Animal husbandry	*Improved feeding*	✓							
		Behaviour changes (less product demand)		✓				✓	✓		
		Afforestation, land protection, biomaterials		✓	✓	✓					

*: Aggregated parameters for GEMINI-E3 model

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Table 6: Adaptation options in each model

			GCAM	TIAM	MUSE	42	GEMINI-E3	ICES	DICE	E3ME
Adaptation measures	*Land*	Water use restrictions						✓		
		Land use adaptation/planning	✓							
	Urban	Additional cooling of buildings	✓							

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2.3 Policies included in the models

All models (can) include some form of emissions mitigation policy instruments, like taxation, emissions target quotas, standards, financial support and global temperature or radiative forcing targets; as well as, with the exception of DICE, some form of energy policy instruments, including taxes and subsidies, energy mix and efficiency targets and specific regulations (e.g. building codes, vehicle technology bans, etc.).

Land policy instruments, on the other hand, such as land protection, production quotas and land-use change emissions taxation are only included in the GCAM model, while TIAM, ICES and DICE can be modified to include some of these instruments. Afforestation targets, as a policy option, are only feasible with minor modifications to some of the models (GCAM, TIAM and DICE).

Finally, carbon border taxes (on imports) and subsidies (on exports) are only included in GEMINI-E3, ICES and (potentially) in TIAM and E3ME; while TIAM and E3ME can also be modified to include some regulation policies (like certifications).

Table 7 summarises policy coverage in the eight documented models.

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Table 7: Mapping of policy options in each model (parentheses imply conditional coverage with adjustments to the model)

		GCAM	TIAM	MUSE	42	GEMINI-E3	ICES	DICE	E3ME
Emissions mitigation policy instruments	Tax	✓	✓	✓	✓	✓	✓	(✓)	✓
	Emissions target / quota (annual)	✓	✓	✓	✓	✓	✓	✓	(✓)
	Emissions target / quota (cumulative)		✓	(✓)	✓	(✓)	✓	✓	(✓)
	Regulations (emissions standards, etc…)	(✓)	✓		✓				(✓)
	Financial supports (e.g. negative emissions, Green Climate Fund)		✓		✓	(✓)	(✓)		(✓)
	Global temperature/radiative forcing target	✓	✓			(✓)	(✓)	✓	
Energy policies instruments	Tax	✓	✓	✓		✓	✓		✓
	Subsidy	✓	✓	✓		✓	✓		✓
	Energy mix target	✓	✓		✓	(✓)	✓		(✓)
	Efficiency target	(✓)	✓		✓	(✓)	✓		(✓)
	Regulations (thermal regulation in buildings, bans on diesel cars, etc.)		✓		✓				(✓)
Land policies instruments	Protected lands	✓							
	Production quotas	✓					(✓)	(✓)	
	Carbon sink pricing / Land use change emissions tax	✓	(✓)						
	Afforestation targets	(✓)	(✓)					(✓)	
Trade policies instruments	Carbon border tax on imports		(✓)			✓	✓		(✓)
	Carbon border supports on exports		(✓)			✓	✓		(✓)
	Regulation policies (certifications, best-available technologies, etc.)		(✓)						(✓)

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2.4 Analysis of implications for SDGs

Table 8 details sixteen of the seventeen SDGs set by the United Nations in 2015 for the year 2030. SDG17 on revitalising global partnership for sustainable development is excluded, as out of the scope of the featured modelling tools. Among these SDGs and with the exception of ICES which can provide insights into all SDGs, the other seven models can deliver indicators to track directly or indirectly eleven of the SDGs.

All of the models are able to report on emissions and therefore on climate action (SDG13). All models can also offer direct insights into affordable and clean energy (SDG7), with the exception of DICE: this entails analyses of renewable energy (all models), access to electricity and primary energy intensity (ICES), traditional biomass use (42 and GCAM), and a full assessment of energy commodities (TIAM, E3ME and MUSE). The same can be said for industry, innovation and infrastructure (SDG9), with the exception of GCAM and 42 that do not feature direct implications. Decent work and economic growth (SDG8) is also covered by five models, mainly via GDP (per capita) growth and employment impacts. SDG2 (zero hunger) is also included in half of the models, be looking into food prices (GCAM, GEMINI-E3 and E3ME) and overall undernourishment (ICES).

Other covered SDGs include SDG1 on poverty prevalence (ICES); SDG3 on health through physical density and life expectancy (ICES) and pollution levels linked to mortality (GCAM, TIAM and E3ME); SDG4 on literacy rate (ICES); SDG5 on gender inequality based on income distribution (E3ME); SDG6 on water and sanitation via freshwater withdrawals (ICES) and groundwater depletion (GCAM); SDG10 on inequalities (E3ME and ICES); SDG11 on sustainable cities (ICES); SDG12 on responsible production and consumption through material productivity (ICES), and footprint impacts (GCAM); SDG15 on life on forest land (ICES and GCAM) and land use change (GCAM); and SDG16 on peace, justice and institution (ICES).

Regarding ICES, a dedicated module aims at offering a comprehensive assessment of future sustainability up to 2030 (with the capacity to extend the analysis to 2050) based upon 27 indicators related to the seventeen SDGs, under different socioeconomic and policy scenarios, by combining the ICES modelling framework with a regression approach (based on historical data) to offer an internally-consistent set-up for analysing future patterns of sustainability indicators and their inter-linkages.

Table 8: Details of SDG (other than SDG13: climate action) measures that can be analysed

Measure	GCAM	TIAM	MUSE	42	GEMINI-E3	ICES	DICE	E3ME
§1. No Poverty						✓		
§2. Zero hunger	✓				✓	✓		✓
§3. Health	✓	✓				✓		✓
§4. Quality education						✓		
§5. Gender equality								✓
§6. Clean water and sanitation	✓					✓		
§7. Affordable and clean energy	✓	✓	✓	✓	✓	✓		✓
§8. Decent work & economic growth		✓			✓	✓	✓	✓
§9. Industry, innovation & infrastructure		✓	✓		✓	✓	✓	✓
§10: Reduced inequalities						✓		✓
§11: Sustainable Cities & Communities						✓		

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§12: Responsible production & consumption	✓					✓		
§13: Climate action	✓	✓	✓	✓	✓	✓	✓	✓
§14: Life below water								
§15: Life on land	✓					✓		
§16: Peace, Justice and institutions						✓		

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2.5 How does each model calculate a mitigation pathway?

Since all eight models are significantly different, they do not operate homogeneously to calculate climate change mitigation pathways. However, some of them feature specific similarities; therefore, the models can be grouped into categories and described by the approach of each category. The models can be sorted into five groups (Nikas et al., 2019):

- **GCAM** and **TIAM** are partial equilibrium models, in that they achieve an equilibrium between the supply and demand for energy in each sector represented, taking into account the changes in energy prices that result from the changes in fuels and technologies used to satisfy energy service demands in these sectors. They are not "full" equilibrium models as they do not consider the subsequent changes in the production and supply costs and demands of all services and goods in the economy—only the energy sectors. TIAM operates on a "perfect foresight" cost-optimisation basis, whereby all consequences of technology deployments, fuel extraction and energy price changes over the entire time horizon are considered when minimising the cost of the energy system, so as to provide energy service demands within specified emissions constraints. By contrast, GCAM operates on a "recursive dynamic" cost-optimisation basis, which means that, rather than considering all future time periods, it solves for the least-cost energy system in a given period, before moving to the next time period and performing the same exercise.
- **MUSE** and **42** are energy system models, and can therefore be considered as a subcategory of the partial equilibrium modelling group, providing a detailed account of the energy sector, i.e. energy technologies and their associated costs, in order to determine the least-cost ways of attaining GHG emission reductions or the costs of alternative climate policies. They both are bottom-up models that assume short-term microeconomic equilibrium on the energy system, which is achieved by iterating market clearance across all of the sector modules, interchanging price and quantity of each energy commodity in each region. MUSE, in addition, is also an agent-based model, as it tries to determine a mitigation pathway by providing an as realistic as possible description of the investment and operational decision making in each geographical region within a sector.
- **GEMINI-E3** and **ICES** are computable general equilibrium (CGE) models, and therefore have a more detailed, multiple-sector representation of the economy and, rather than seeking optimal policies, they consider the impacts of specific policies on economic, social and environmental parameters. Their operation is similar to that of GCAM and TIAM, but differs in that market equilibrium is assumed to take place in the entire economy. Their richer representation of the economy comes at a cost in that the growth of the economy is harder to model and its structure more complex; as such, they require calibration to data on national and international socio-accounting information, as well as input in the form of a series of elasticities of substitution. Contrary to all other models, they also calculate economic indices endogenously.
- Although **DICE** can also be considered as part of the CGE family, it is distinguished as an optimal growth, or welfare optimisation, or neoclassical model, which does not feature the same level of sectoral or geographic detail (it exclusively covers the entire global economy). It determines the climate policy and investment levels that maximise welfare (future against present consumption) over time, by identifying the emission abatement levels for each time step; its social welfare function represents the world's well-defined set of preferences and accordingly ranks different consumption paths, with welfare increasing in per capita consumption for each generation but with diminishing marginal utility of consumption (the wealthier the world is, the less valuable an additional unit of consumption is).

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- Finally, **E3ME** is a macroeconometric model. Quite like CGE models, it is quite detailed in terms of energy technologies and geographic scope, but differs in that it does not assume that consumers and producers behave optimally or that markets clear and reach equilibrium in the short term. Instead, it uses historical data and econometrically estimated parameters and relations to dynamically and more realistically simulate the behaviour of the economy, by assuming that markets achieve equilibrium in the longer run.

2.6 Example use-cases for each model

Table 9: Key examples of policy-relevant questions addressed by each model in recent years

Model	Example study	Research question/focus	Selected key findings
GCAM	Van de Ven et al. (2019)	Integrated policy assessment and optimisation over multiple sustainable development goals in Eastern Africa	The analysis shows that support for biogas technology should be prioritised in both the short and long term, while financing liquefied petroleum gas (LPG) and ethanol technologies also has synergetic climate, health and energy access benefits. Instead, financing PV technologies is mostly relevant for improving energy access, while charcoal and to a lesser extend fuelwood technologies are relevant for curbing GHG emissions if their finance is linked to land policies.
TIAM	Realmonte et al. (2019)	An investigation of the role of Direct Air Capture (DAC) in meeting global 1.5°C and 2°C pathways	DAC can reduce the policy costs of mitigation in the near-term, but there are many uncertainties about its scale-up potential and, if we ease mitigation efforts and rely on DAC, even if it does not deliver large-scale removals, we will overshoot the Paris climate goals.
MUSE	Kerdan et al. (2019a)	Gas infrastructure pathways for the southern states of Brazil	Results suggest that, due to the expected increase in regional gas demand in South Brazil, the existing gas infrastructure would require additional investments. Depending on the renegotiation outcomes between Brazil and Bolivia (i.e. either maintaining constant, halving, or halting the Bolivian import of gas), natural gas demand could be covered by a share of alternative supply options, such as an increase in pre-salt production, LNG imports and imports from a new Argentinian pipeline.
42	Ivanter et al. (2018)	How to Boost the Development of the Russian Economy: Priority Actions	A set of priority directions of the economic policy, primarily in investment activity, development of the domestic market, as well as financial and organisational support for the suggested actions.
GEMINI-E3	Babonneau et al. (2018a)	The evaluation of the Paris Intended Nationally Determined Contributions (INDCs) and the design of fair agreements concerning additional abatements up to 2050.	Results confirm the weakness of INDC pledges. Nevertheless, it shows that, with political determination, an equitable burden-sharing agreement can be achieved with very reasonable costs for all nations of approximately 0.8% of total discounted household consumption. With a more ambitious 1.5°C target, the global cost is

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			multiplied by a factor of four revealing the stringency of such an objective.
ICES	Campagnolo & Davide (2019)	An assessment of climate mitigation co-benefits or side-effects on poverty and inequality, in respect to the Paris Agreement.	A full implementation of the emission reduction contributions, stated in the NDCs, is projected to slow down the effort to reduce poverty by 2030 (+4.2% of the population below the poverty line compared to the baseline scenario), especially in countries that have proposed relatively more stringent mitigation targets and suffer higher policy costs. Conversely, the impact of climate policy on inequality shows opposite sign but remains very limited. If financial support for mitigation action in developing countries is provided through an international climate fund, the prevalence of poverty will be slightly reduced at the aggregate level, but the country-specific effect depends on the relative size of funds flowing to beneficiary countries and on their economic structure.
DICE	González-Eguino et al. (2016)	Implications of permafrost thawing for climate change control.	The fossil fuel and industrial CO_2 emissions need to peak 5–10 years earlier and the carbon budget needs to be reduced by 6–17% to offset this additional source of warming. The required increase in carbon price implies a 6–21% higher mitigation cost to society compared to a situation where emissions from permafrost are not considered. Including other positive climate feedbacks, currently not accounted for in integrated assessment models, could further increase these numbers.
E3ME	Gramkow and Anger-Kraavi (2019)	Exploring a transformation of Brazil's economy, with a focus on manufacturing sectors, while contributing to the Paris targets	The correct mix of green stimulus can help modernise and decarbonise the Brazilian manufacturing sectors and the country's economy grow faster (by up to 0.42% compared to baseline) while its CO_2 emissions decline (by up to 14.5% in relation to baseline). Investment levels increase, thereby strengthening exports' competitiveness and alleviating external constraints to long-term economic growth in net terms. Scaling up green fiscal stimulus in manufacturing sectors globally needs to be considered as one of the main policy measures helping with transformation to a low-carbon economy, especially in the developing world.

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3 Model validation

Regarding the use of models such as those included in WP7 (and indeed throughout the PARIS REINFORCE project), a legitimate question has been raised, both in the literature and in the policy world, around the levels of trust that people (whether scientists, policymakers, or other stakeholders) should have in these models and their outputs (Doukas and Nikas, 2020). That is, especially, considering the underlying assumptions driving them (Kelly and Kolstad, 1999) and uncertainty ranges (Doukas et al., 2018), as well as the extent to which these are communicated alongside the results.

It is unavoidable that the models used in PARIS REINFORCE cannot provide a complete representation of the world, owing to the fact that in many ways the future is unknown, and furthermore there is incomplete knowledge of past dynamics governing energy, agricultural, land and environmental systems that are represented by these models.

Despite this challenge, the models used in PARIS REINFORCE are intended to be trusted, and seen as useful and valid, by both the scientific community and—equally if not more importantly—stakeholders such as policy- and decision-makers, who will plan low-carbon strategies on their basis. Here we detail the steps both that have been applied in developing and using the models, as well those that will be applied in the context of the project, in order that such trust and validation is achieved.

The workflow to be followed in PARIS REINFORCE includes the following steps, as also presented in Figure 1, based on the relevant literature on evaluation and validation of integrated assessment models and drawing from the primary elements of (Schwanitz, 2013):

- **Documentation** of models' capabilities, in terms of geographic, policy, sectoral, technological, emissions, and socioeconomic coverage, in technical and non-expert-friendly language, for both the academic community to evaluate and other stakeholder groups to comprehend and appreciate the extent to which models can be used to respond to policy questions and concerns. A major part of this documentation step is this deliverable itself, and its representation on the I^{2}AM PARIS platform.
- **Communication** of these capabilities, as well as of the extent to which these models are validated, referenced, benchmarked, and evaluated, and therefore trustworthy. This includes a process of presenting the modelling approaches and preliminary results to stakeholders, a discussion of the types of inputs and outputs the models produce as well as of how they produce these outputs, and a co-design of the entire research process to ensure transparency and policy demand orientation. A central part of WP7 is the series of two EU-wide stakeholder workshops, featuring sessions on global issues, to undertake this process.
- **Benchmarking and harmonisation** of inputs, as part of validity checks of the employed models, with the aim to ensure that they are in line with the most up-to-date verified information as well as harmonised in the multi-model analyses and inter-comparisons envisaged in the project, so as to allow mapping the resulting ranges exclusively onto the models' diversity (see Giarola et al., which explicitly reports on this harmonisation process, and Sognnaes et al., which explores inter-model differences in scenarios).
- **Diagnostics** runs, to check that each model's responses to key input variable changes are in line with common expectations and compared to other results and models covering the globe and/or a priori defined 'stylised' behaviours (see Giarola et al.).
- **Iteration** of this workflow, with experts and non-expert stakeholders, to document and discuss results with them, allowing them to appreciate the behaviours of the models under increasingly stringent mitigation

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scenarios, and why the models respond in the way that they do.

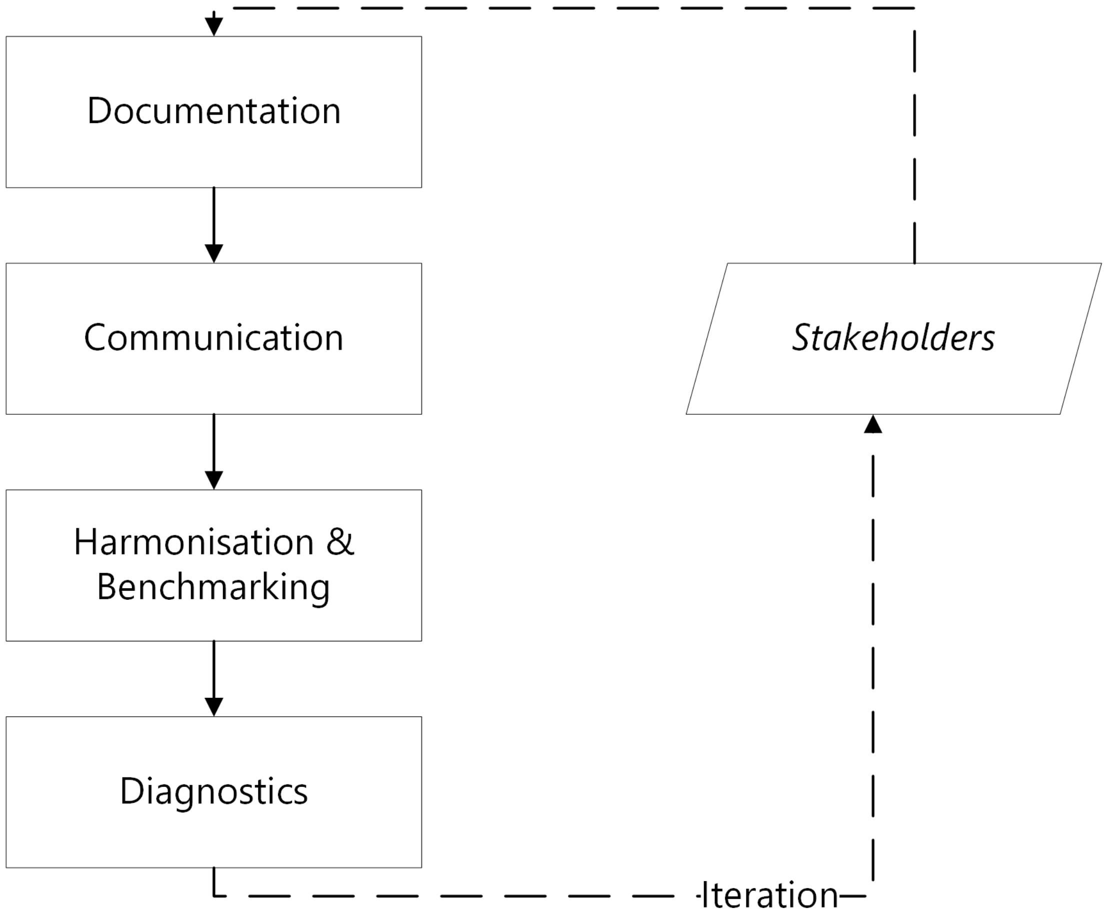

Figure 1: Model validation process in WP7

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4 Detailed documentation of each model

The following eight subsections outline the details of each of the documented models individually, to elaborate on the information summarised in Section 2 above. The structure of each model's documentation has been kept harmonised, to the extent possible, for ease of reference, and comprises the following sections:

1. Short model overview
2. Key features of the model (including regions covered, energy system representation, economic/sectoral structure and time horizon, where applicable)
3. Emissions covered and climate module (if relevant)
4. Socioeconomic dimensions
5. Model calibration
6. Main mitigation and adaptation (where applicable) measures and technologies
7. Economic rationale and model solution
8. Key parameters
9. Policy questions that can be addressed, including implications for SDGs
10. Recent use cases

4.1 The Global Change Assessment Model (GCAM)

4.1.1 Short overview

The Global Change Assessment Model (GCAM) is a global integrated assessment model that represents both human and Earth system dynamics. It explores the behaviour and interactions between the energy system, agriculture and land use, the economy and climate. The role of GCAM is to bring multiple human and physical Earth systems together in one place to provide scientific insights that would not be available from the exploration of individual scientific research lines. The model components provide a faithful representation of the best current scientific understanding of underlying behaviour.

GCAM allows users to explore what-if scenarios, quantifying the implications of possible future conditions. These outputs are not predictions of the future; they are a way of analysing the potential impacts of different assumptions about future conditions. GCAM reads in external "scenario assumptions" about key drivers (e.g., population, economic activity, technology, and policies) and then assesses the implications of these assumptions on key scientific or decision-relevant outcomes (e.g., commodity prices, energy use, land use, water use, emissions, and concentrations).

It is used to explore and map the implications of uncertainty in key input assumptions and parameters into implied distributions of outputs, such as GHG emissions, energy use, energy prices, and trade patterns. Techniques include scenarios analysis, sensitivity analysis, and Monte Carlo simulations.

GCAM has been used to produce scenarios for national and international assessments ranging from the very first IPCC scenarios (Response Strategies Working Group, 1990) through the present Shared Socioeconomic Pathways (SSPs) (Calvin et al., 2017).

4.1.2 Key features of the GCAM model

GCAM takes in a set of assumptions and then processes those assumptions to create a full scenario of prices, energy and other transformations, and commodity and other flows across regions and into the future. The energy, agriculture and land use, economy and climate systems are interconnected and interact with each other (Figure

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2). The interactions between these different systems are modelled as one integrated whole.

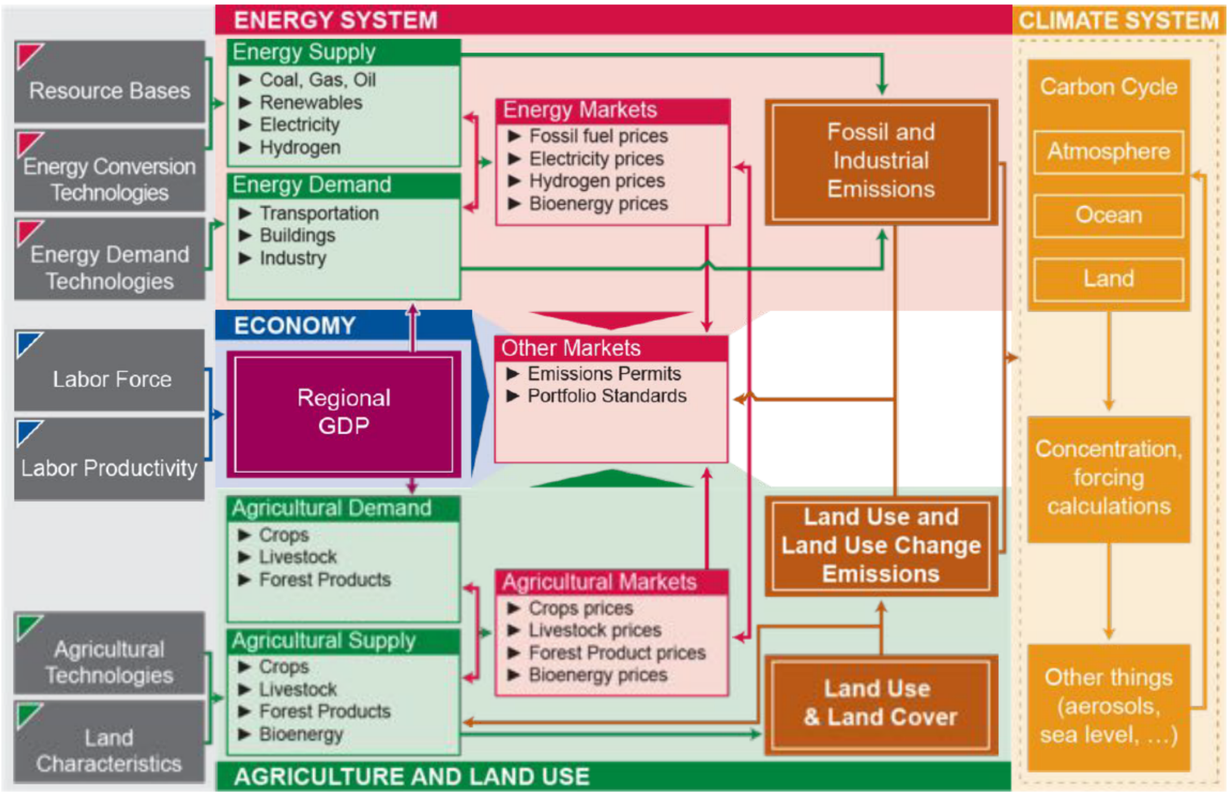

Figure 2: Representation of GCAM Core functioning

Source: https://jgcri.github.io/gcam-doc/overview.html

4.1.2.1 Geographic coverage

The GCAM core represents the entire world, but it is constructed with different levels of resolution for each of these different systems. The energy-economy system operates at 32 geopolitical regions globally (Table 10), water withdrawals are tracked for 235 hydrologic basins worldwide, and to avoid overlap between geopolitical regions and hydrologic basins, agriculture and land use is calibrated for 384 regions worldwide (Figure 3).

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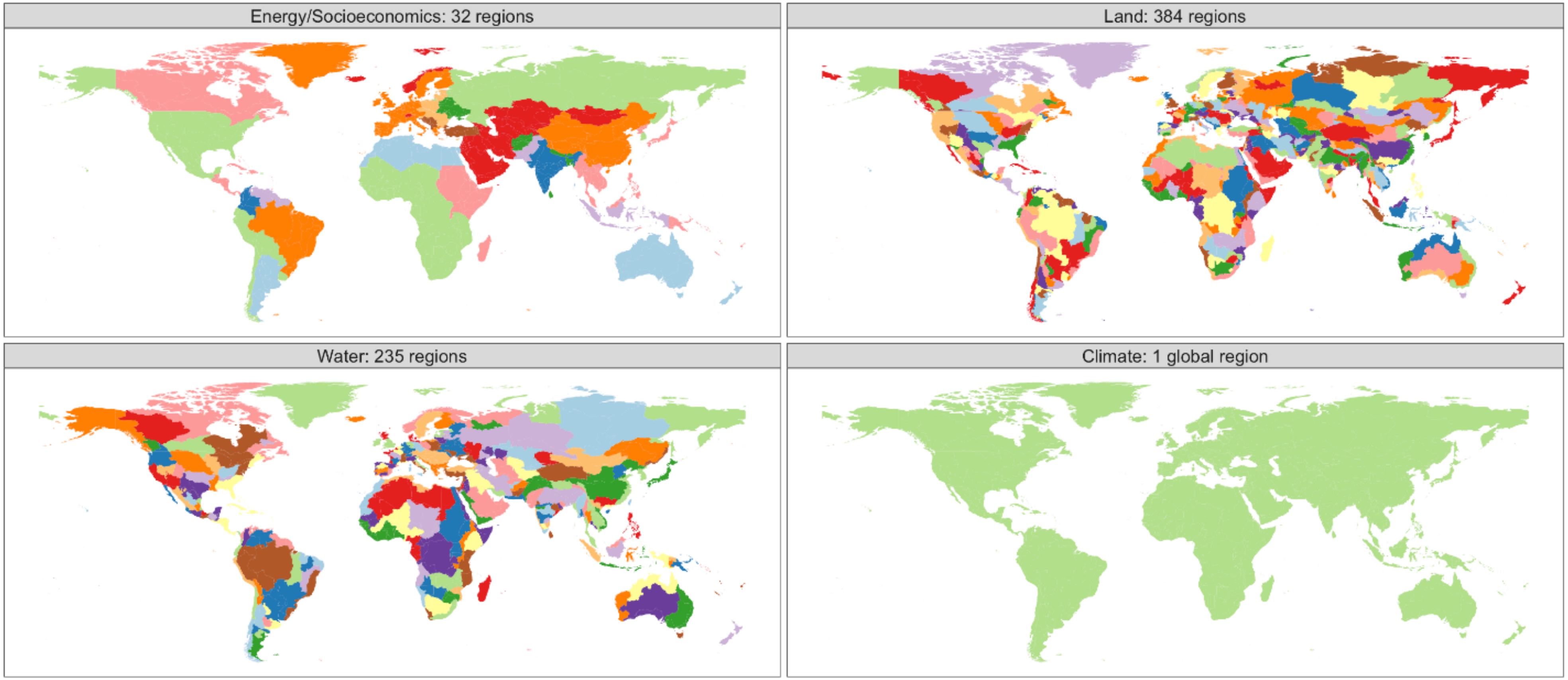

Figure 3: GCAM regional mapping

Source: https://jgcri.github.io/gcam-doc/overview.html

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Table 10: Countries included in each region in GCAM

Geographic region	Countries
Eastern Africa	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda
Northern Africa	Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia
Southern Africa	Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe
Western Africa	Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo
Argentina	Argentina
Australia and New Zealand	Australia, New Zealand
Brazil	Brazil
Canada	Canada
Central America and the Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines
Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan
China	China
Colombia	Colombia
EU-12	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia
EU-15	Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom
Eastern Europe	Belarus, Moldova, Ukraine
European Free Trade Association	Iceland, Norway, Switzerland
Non-EU Europe	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey
India	India
Indonesia	Indonesia
Japan	Japan
Mexico	Mexico
Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen
Pakistan	Pakistan
Russia	Russia
South Africa	South Africa
Northern South America	French Guiana, Guyana, Suriname, Venezuela
Southern South America	Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay
South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal
Southeast Asia	American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic People's Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa
South Korea	South Korea
Taiwan	Taiwan
USA	United States

4.1.2.2 Energy system detail

The structure of the energy system consists of four main elements: resource production, energy transformation, final energy carriers and end-use (Figure 4). It also tracks international trade in energy commodities. All the different elements of GCAM interact through market prices and physical flows of, for example, electricity.

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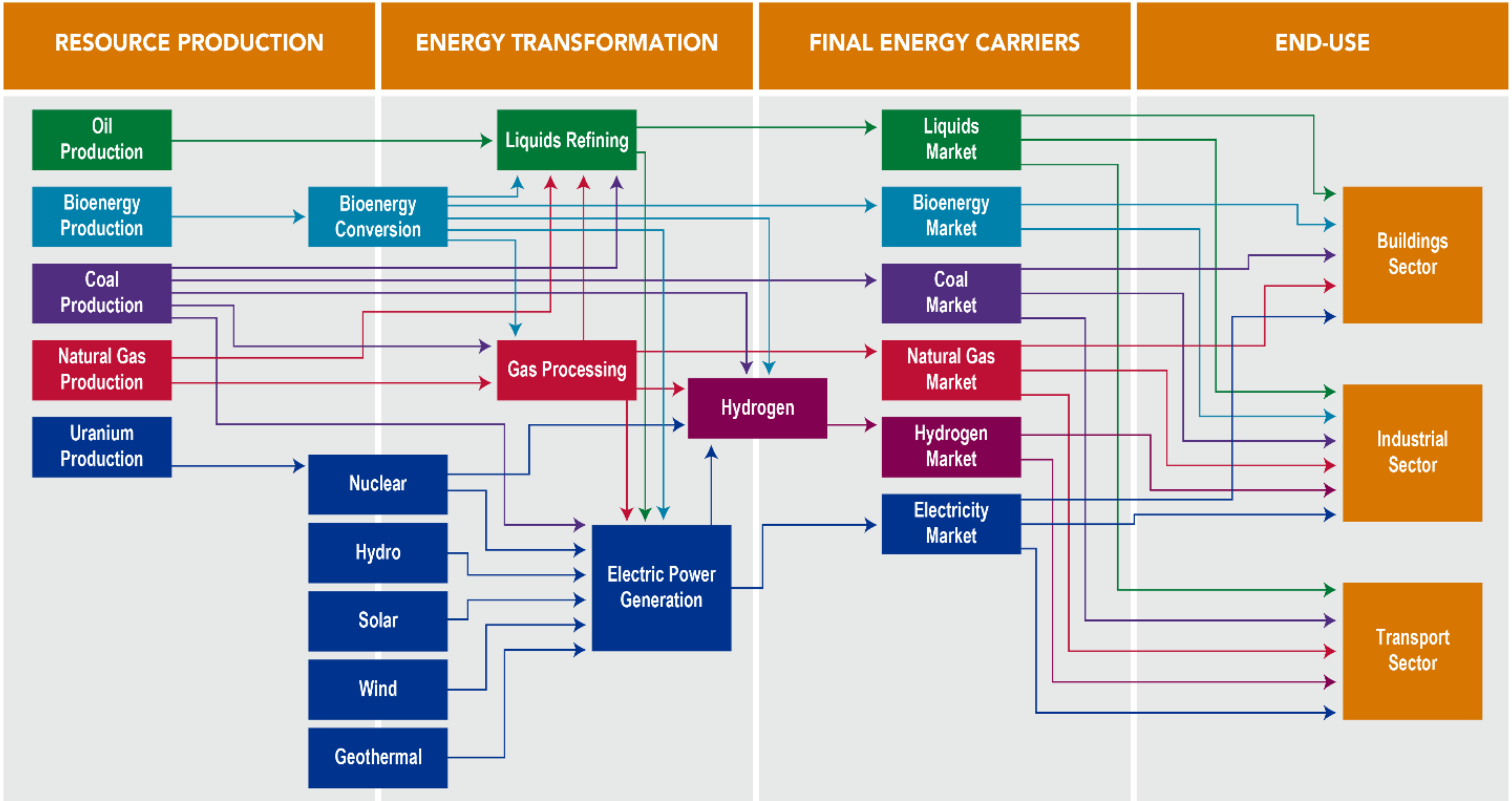

Figure 4: Structure of Energy system in GCAM

Source: https://jgcri.github.io/gcam-doc/energy.html

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4.1.2.3 Land and agricultural system detail

Within each of the land regions shown in Figure 3, land is categorised into approximately a dozen types based on cover and use. In GCAM, competing uses of land are nested within land nodes. Within each land node, it is generally assumed to be easier to substitute products. Among arable land types, further divisions are made for lands historically in non-commercial uses (forests and grasslands) and commercial land uses (commercial forests and croplands). Production of approximately twenty crops is currently modelled, with specific yields depending on the land region and management type (with and without irrigation, high and low fertiliser).

4.1.3 Climate module & emissions granularity

GCAM uses a global climate carbon-cycle climate module, Hector (Calvin et al., 2019), an open-source, object-oriented, reduced-form global climate carbon-cycle model that represents the most critical global-scale earth system processes. At every time step, emissions from GCAM (Table 11) are passed to Hector. Hector converts these emissions to concentrations and calculates the associated radiative forcing and the response of the climate system (e.g., temperature, carbon-fluxes, etc.).

Table 11: List of gases and corresponding sectors included in the GCAM model and passed to HECTOR.

Gas	Sector	Gas	Sector
CO_2**	AgLU***, Energy	NH_3	AgLU, Energy
CH_4	AgLU, Energy, Industrial Processes, Urban Processes	SO_2	AgLU, Energy, Industrial Processes
N_2O	AgLU, Energy, Industrial Processes, Urban Processes	CO	AgLU, Energy, Industrial Processes
SF_6	Energy, Industrial Processes	BC	AgLU, Energy
HFCs	Energy, Industrial Processes, Urban Processes	OC	AgLU, Energy
		NO_x	AgLU, Energy, Industrial Processes
		NMVOC	AgLU, Energy, Industrial Processes, Urban Processes
		C_2F_6	Energy, Industrial Processes
		CF_4	Industrial Processes, Urban Processes

* *Most of these gases also have positive or negative indirect effects on radiative forcing*
***CO_2 emissions from the AgLU sector are separate from CO_2 emissions from the Energy sector. Any change in atmospheric carbon occurs as a function of anthropogenic fossil fuel and industrial emissions, land-use change emissions and the atmosphere-ocean and atmosphere-land carbon fluxes.*
****AgLU = Agriculture and Land Use*

Hector has a three-part main carbon cycle: a one-pool atmosphere, three-pool land, and four-pool ocean (Figure 5). The atmosphere consists of one well-mixed box. The ocean consists of four boxes, with advection and water mass exchange simulating circulation. The high-latitude surface ocean takes up carbon from the atmosphere, while the low-latitude surface ocean off-gases carbon to the atmosphere. The land consists of a user-defined number of biomes or regions for vegetation, detritus and soil. The vegetation takes up carbon from the atmosphere while the detritus and soil release carbon back into the atmosphere. The earth pool is continually debited with each time step to act as a mass balance check on the carbon system. Hector actively solves the inorganic carbon system in the surface ocean, directly calculating air– sea fluxes of carbon and ocean pH. It reproduces the global historical trends of atmospheric [CO_2], radiative forcing, and surface temperatures.

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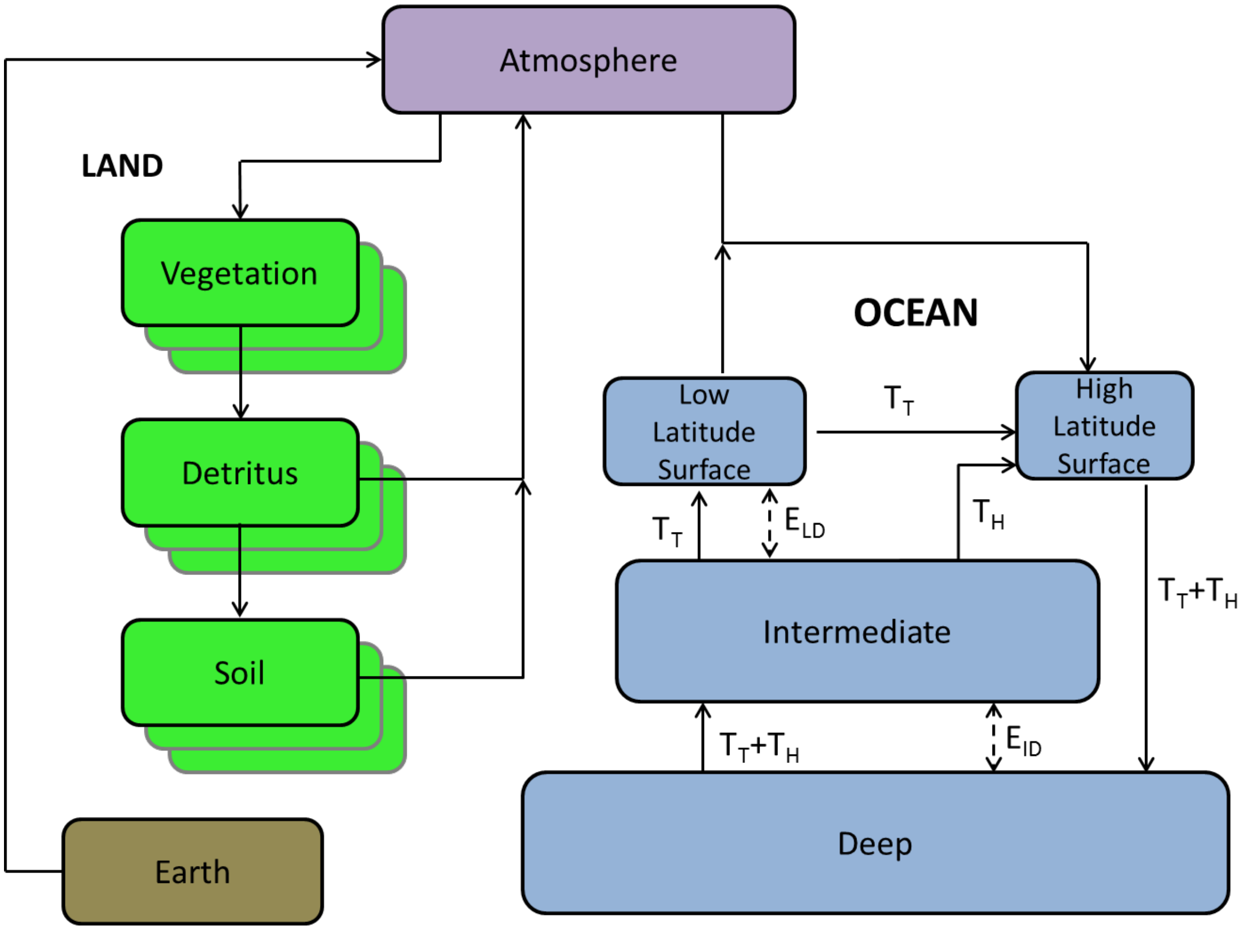

Figure 5: Representation of Hector's carbon cycle, land, atmosphere, and ocean used in GCAM

Source: https://jgcri.github.io/gcam-doc/hector.html

4.1.4 Socioeconomic dimensions

4.1.4.1 Economic growth

The socioeconomic components of GCAM set the scale of economic activity and associated demands for model simulations. Assumptions about population and per capita GDP growth for each of the 32 geo-political regions together determine the GDP. Population and economic activity are used in GCAM to transfer information to other GCAM components, and are determined exogenously.

GCAM's inputs include information on population and the rate of per capita income growth for each of the energy-economic regions. Each scenario requires assumptions about population and per capita GDP growth for future time periods, for example those of the SSPs. The macro-economic module takes both of these to produce overall GDP in each GCAM energy-economic region, where the regional GDP is calculated using a simple one-equation model:

$$GDP_{r,t+1} = POP_{r,t+1}\left(1 + GRO_{r,t}\right)^{tStep}\left(\frac{GDP_{r,t}}{POP_{r,t}}\right)P_{r,t+1}^{\alpha}$$

Where r stands for region, t for period, $t\ Step$ = number of years in the time step (5 for GCAM), $GDP_{r,t}$ for GDP in region r in period t, $POP_{r,t}$ for population in region r in period t and $GRO_{r,t}$ for annual average per capita GDP growth rate in region r in period t.

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4.1.4.2 Industrial sector growth

Growth in industrial sectors is based on a pre-defined GDP elasticity which decreases over time, thus assuming saturation of industrial demand with rising incomes. The values of these elasticities vary per region and between different SSPs. Apart from a GDP elasticity, industrial demand also depends on an assumed price elasticity for industrial energy use.

4.1.4.3 Transport sector growth

Per capita demand for passenger transport depends on an assumed GDP per capita elasticity and price elasticity, which means that more transport services are demanded at higher incomes and cheaper transport. However, there is also a time cost involved in transport, which increases proportionally with GDP per capita, and which is summed to the capital and energy costs of transport. This means that, at higher incomes, demand for passenger transport slowly saturates due to the price elasticity multiplied by the increasing costs of time. Also, demand shifts to faster ways of transport, for which time costs are lower. Demand for freight transport, like for industrial sectors, depends on an assumed GDP elasticity and price elasticity.

4.1.4.4 Building sector growth

Demand for energy services in residential and commercial buildings is primarily by total building floor space, which is driven by GDP per capita, and saturates at a given maximum value, defined per region. Per unit of floor space, demand for energy services increases over time depending on the relative price of the service, and the difference between the base year saturation and the defined maximum saturation for a certain service. For heating and cooling services, the maximum saturation depends on regionally explicit heating and cooling degree days.

4.1.4.5 Demand for agricultural commodities

Per capita demand for crops, animal products and forest products depend on assumed income and price elasticities. By default, price elasticities for crops and forest products are equal to 0 throughout the future, which means that these basic needs will be fulfilled, independent of commodity prices. Demand for animal products depends on the price of such products, as well as incomes, and assumptions in income elasticities vary strongly between different SSPs.

4.1.5 Mitigation/adaptation measures and technologies

GCAM is a technology-rich model that represents most major fossil fuel and low-carbon technologies that are envisaged to be available for at least the first half of the 21st century. By simulating the substitution of low-carbon for high-carbon technologies in response to their relative costs, as well as emissions constraints and/or carbon prices, the GCAM model simulates mitigation through a large set of different measures (see model template).

Table 12: Main mitigation options in GCAM

Upstream	
Synthetic fuel production	***Hydrogen production***
Coal to gas with CCS Coal to liquids with CCS Gas to liquids with CCS Biomass to liquids (with and without CCS)	Electrolysis Coal to hydrogen with CCS Gas to hydrogen with CCS Thermal splitting (nuclear)
Electricity and heat	
Electricity generation	***Heat generation***
Coal with CCS Gas with CCS Nuclear (fission and fusion)	Coal with CCS Gas with CCS Oil with CCS

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Hydro Biomass (with and without CCS) Geothermal Solar PV Solar CSP Wind (onshore) Marine	Geothermal Biomass Biomass with CCS
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Hybrid electric vehicles Fully electric vehicles Hydrogen fuel cell vehicles Biofuels in fuel mix	Electric Hydrogen Efficiency
Air	***Marine***
Biofuels in fuel mix	Gas Hydrogen Biofuels Efficiency
Buildings	
Heating	***Lighting***
Gas replacing coal / oil Biofuels Electricity Efficiency	
Behaviour	***Cooling***
Behavioural change	Electricity
Industry	
Process heat	***CHP***
Gas replacing oil / coal Biomass Hydrogen Electricity	Gas replacing oil / coal Biomass
Agriculture	
Land & Animal husbandry	***Behaviour***
Land yield maximisation Improved feeding practices	Behavioural changes (less product demand)
Land Use, Land Use Change, Forestry	
Afforestation Land production Biomaterials	

Also, certain assumption sets can be loaded for future crop yields, heating and cooling degree days, which are consistent with a certain temperature target. Through these assumptions, the model adapts to the simulated reality through the allocation of agricultural production, and building service demands.

4.1.6 Economic rationale and model solution

The core operating principle for GCAM is that of market equilibrium. The representative agents in the modules use information on prices and make decisions about the allocation of resources. They represent, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents indicate their intended supply and/or demand for goods and services in the markets. GCAM solves for a set of market prices so that supplies and demands are balanced in all these markets across the model (Figure 6); in other words, market equilibrium is assumed to take place in each one of these markets (partial equilibrium), and not in the entire economy across all markets (general equilibrium). The GCAM solution process is the process of iterating on market prices until this equilibrium is reached. Markets

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exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

As an example, in any single model period, GCAM derives a demand for natural gas starting with all of the uses to which natural gas might be put, such as passenger and freight transport, power generation, hydrogen production, heating, cooling and cooking, fertiliser production, and other industrial energy uses. Those demands depend on the external assumptions about, for example, electricity generating technology efficiencies, but also on the price of all of the commodities in the model. GCAM then calculates the amount of natural gas that suppliers would like to supply given their available technology for extracting resources and the market price. The model gathers this same information for all of the commodities and then adjusts prices so that in every market during that period supplies of everything from rice to solar power match demands.

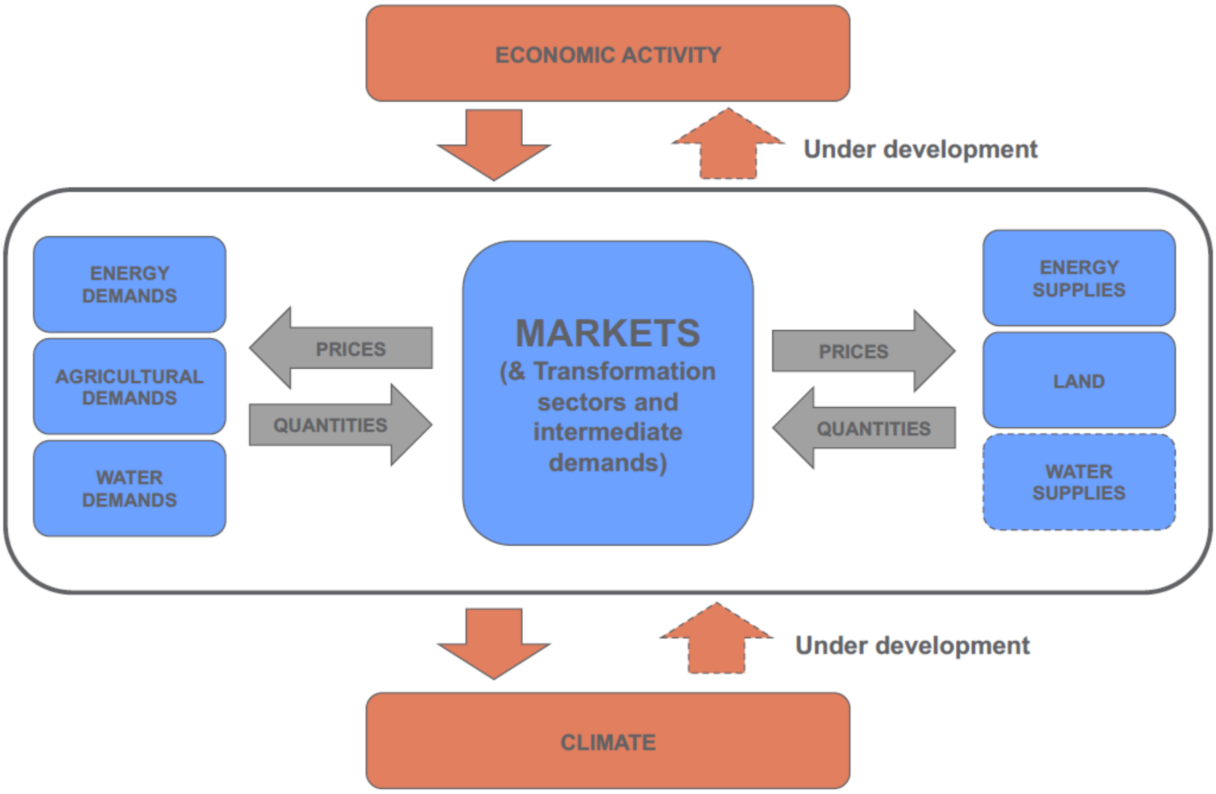

Figure 6: Conceptual Schematic of the Operation of the GCAM Core
Source: https://jgcri.github.io/gcam-doc/overview.html

GCAM is a dynamic recursive model, meaning that decision-makers do not know the future when making a decision today, as opposed to other optimisation models, which assume that agents know the future with certainty when they make decisions. After it solves each period, the model then uses the resulting state of the world, including the consequences of decisions made in that period—such as resource depletion, capital stock retirements and installations, and changes to the landscape—and then moves to the next time step and performs the same exercise. The GCAM version used is typically operated in five-year time steps with 2100 as the final calibration year. However, the model has flexibility to be operated at a different time horizon through user-defined parameters.

While the agents in the GCAM model are assumed to act towards maximising their own self-interest, the model as a whole is not performing an optimisation calculation. In fact, actors in GCAM can make decisions that "seemed like a good idea at the time", but which are not optimal from a larger social perspective and which the decision

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maker would not have made had the decision maker known what lay ahead in the future. For example, the model's actors do not know about future climate regulations, and could install fossil fuel power in the years preceding the implementation of such policies. Also, stated preferences by agents for certain technologies (e.g. transport modes) are calculated in the base year and such preferences are persistent into the future (their evolution can be changed by the user), preventing the solution to be completely cost-minimising or profit-maximising.

4.1.7 Key parameters

Key scenario assumptions for the GCAM core include socioeconomics (population, labour participation, and labour productivity); energy technology characteristics (e.g. costs, performance, water requirements); agricultural technology characteristics (e.g. crop yields, costs, carbon contents, water requirements, fertiliser requirements); energy and other resources, such as fossil fuels, wind, solar, uranium and groundwater; and policies, including emissions constraints, renewable portfolio standards, etc.

Key scenario results (outputs) from the GCAM model include an analysis of the energy system (energy demands, flows, technology deployments, and prices throughout); prices and supplies of all agricultural and forest products, land use and land use change; water demands and supplies for all agricultural, energy, and household uses; and emissions for 24 greenhouse gases and short-lived species (CO_2, CH_4, N_2O, halocarbons, carbonaceous aerosols, reactive gases, and sulphur dioxide).

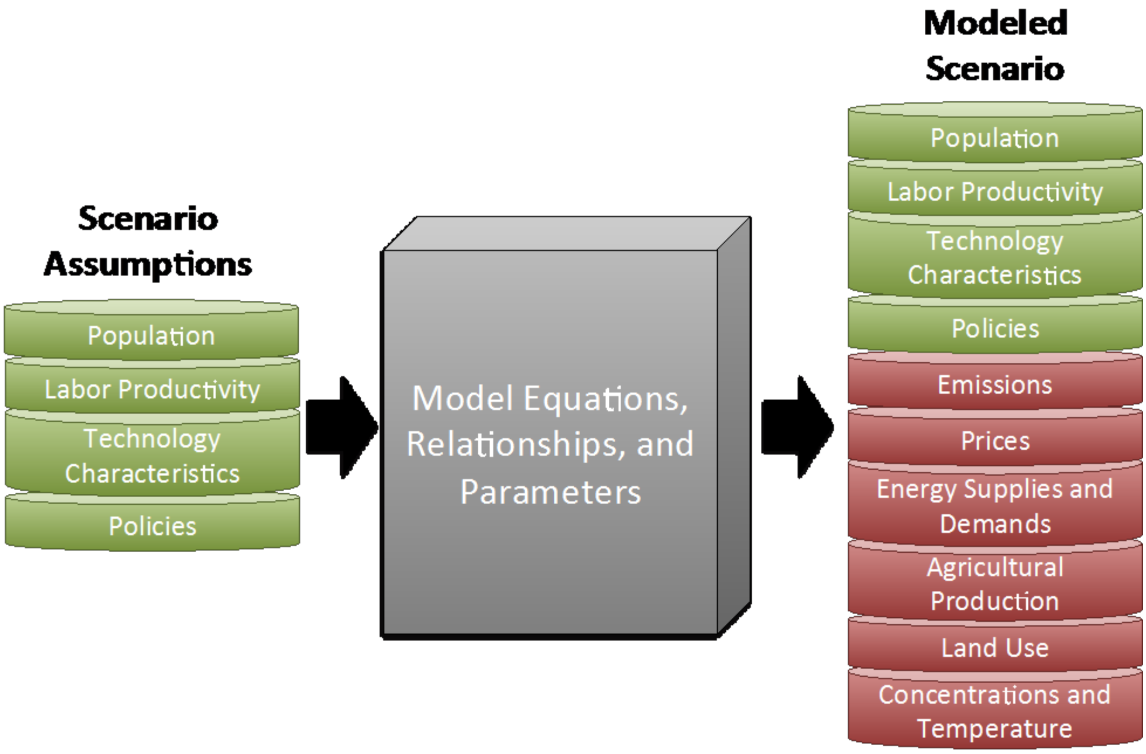

Figure 7: GCAM scenario assumptions and modelling outputs

Source: https://jgcri.github.io/gcam-doc/overview.html

Outcomes in GCAM depend strongly on the assumptions made for socioeconomic, techno-economic, and agronomic parameters. While many of these parameters matter for the outcomes from the model, some can be identified as the most relevant ones, given the purpose of GCAM in the framework of the PARIS REINFORCE project:

- Global and national GHG reduction targets

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- Global and national afforestation targets
- Future demand scenarios for energy services and agricultural products
- Future cost paths for renewable energy and CCS technologies

Parameters can be revised and updated in the framework of the PARIS REINFORCE project, following the feedback of local experts (stakeholder engagement), the comparative assessment with other modelling experiences, and the discussion with the partners (modellers).

4.1.8 Policy questions and SDGs

4.1.8.1 Key policies that can be addressed

One of GCAM's uses is to explore the implications of different future policies. There are a number of types of policies that can be easily modelled in GCAM:

Emissions-related policies: There are three main policy approaches that can be applied in GCAM to reduce emissions of CO_2 or other GHGs: carbon/GHG prices, emissions constraints, or climate constraints. In all cases, GCAM implements the policy approach by placing a price on emissions. This price then filters down through all systems in GCAM and alters production and demand. For example, a price on carbon would put a cost on emitting fossil fuels. This cost would then influence the cost of producing electricity from fossil-fired power plants that emit CO_2, which would then influence their relative cost compared to other electricity generating technologies and increase the price of electricity. The increased price of electricity would then make its way to consumers that use electricity, decreasing its competitiveness relative to other fuels and leading to a decrease in electricity demand.

- Carbon or GHG prices: GCAM users can directly specify the price of carbon or GHG emissions. Given a carbon price, the resulting emissions will vary depending on other scenario drivers, such as population, GDP, resources, and technology.
- Emissions constraints: GCAM users can specify the total amount of (CO_2 or other GHG) emissions as well. GCAM will then calculate the price of carbon needed to reach the constraint in each period of the constraint.
- Climate constraints: GCAM users can specify a climate variable (e.g. concentration or radiative forcing) target for a particular year. Users determine whether that target can be exceeded prior to the target year. GCAM will adjust carbon prices in order to find the least-cost path to reaching the target.

Emissions prices of different GHGs can be linked together for a multi-gas policy. Additionally, markets in GCAM can be set for any emission species (e.g., CH_4-only market, NO_x market, etc.). In addition to identifying emission prices as one measure of cost, GCAM employs the "deadweight loss" approach to measuring welfare loss from emissions mitigation efforts through carbon pricing.

Energy production policies: There are times when users would like to explore the implications of a constraint on production or a minimum production requirement. This capability allows GCAM users to model policies such as renewable portfolio standards and biofuels standards. Across sectors, these constraints must be applied as quantity constraints, but they can be applied as share constraints within individual sectors (e.g. fraction of electricity that comes from solar power). In implementing these policies, users can set either a lower bound or an upper bound. The model will solve for the tax (upper bound) or subsidy (lower bound) required to reach the given constraint.

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Land use policies

- Protected Lands: With this policy, GCAM users can set aside a fraction of natural land, removing it from economic competition. This land cannot be converted to crops, pasture, or any other land type. This is similar to real-world policies such as reducing emissions from deforestation and forest degradation (REDD).
- Valuing carbon in land: When applying a price on carbon through any of the emissions-related policy approaches, GCAM users can choose whether that price extends to land use change CO_2 emissions. This policy is modelled as a subsidy to land-owners for holding carbon stocks as opposed to a price on the emissions themselves.
- Bioenergy constraints: GCAM users can impose constraints on bioenergy within GCAM. Under such a policy, GCAM will calculate the tax or subsidy required to ensure that the constraint is met.

4.1.8.2 Implications for other SDGs

GCAM does not automatically calculate the implications on non-climate SDGs of its least-cost energy system to meet prescribed climate or emissions constraints. However, it is possible to use its outputs and calculate the predictions for certain indicators framed in the SDG agenda.

Table 13: Capacity of the GCAM model to address non-climate SDGs

SDGs	GCAM
§2. Zero hunger (e.g., food prices, shortages)	Food prices by region
§3. Health (e.g., air-pollution related mortality)	Mortality due to air pollutants
§6. Clean water and sanitation (e.g., groundwater depletion)	Groundwater depletion by river basin
§7. Affordable and clean energy (e.g., traditional biomass use, %renewable energy)	Traditional biomass use and renewable energy penetration
§12: Responsible production & consumption (e.g., % recycled waste, embedded emissions)	Footprint impact of consumption
§15: Life on land (e.g., land use for forests, rate of land use change)	Land use for forests and rate of land use change

4.1.9 Recent use cases

Table 14: List of recent publications using the GCAM model

Paper	Topic	Key findings
(Huang et al., 2019)	Global agricultural green and blue water consumption under future climate and land use changes	Global crop green water consumption will increase by 12% in 2090s when compared with that in 1971–2000, and climate change will dominate over land use change in determining the trend of global crop green water consumption. However, expansion in global irrigated area will dominate the changing trend of global crop blue water consumption which increases 70% by 2090s, especially in regions with significant irrigated land expansion (e.g. northern Africa, central Asia, China, Mexico, the Middle East, Russia, southern Asia, and Argentina). Furthermore, global crop blue water dependence will increase under climate and land use

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		changes, especially in arid regions.
(Markandya et al., 2018)	Health co-benefits from air pollution and mitigation costs of the Paris Agreement	The health co-benefits substantially outweighed the policy cost of achieving the 2°C target. The ratio of health co-benefit to mitigation cost ranged from 1.4 to 2.45, depending on the scenario. At the regional level, the costs of reducing GHG emissions could be compensated with the health co-benefits alone for China and India, whereas the proportion the co-benefits covered varied but could be substantial in the European Union (7–84%) and USA (10–41%), respectively. Finally, we found that the extra effort of trying to pursue the 1.5°C target instead of the 2°C target would generate a substantial net benefit in India (US$3.28–8.4 trillion) and China ($0.27–2.31 trillion).
(Fawcett et al., 2015)	Understanding what the INDCs collectively deliver in terms of reducing the probability of the highest levels of global mean surface temperature change and improving the odds of limiting temperature change to under 2°C relative to preindustrial levels	To limit warming to any level, CO_2 emissions at the global level must ultimately be brought to zero. If emissions are not brought swiftly to zero beyond 2100, the chances of extreme temperature change after 2100 could be much higher and the chance of limiting warming to 2°C much lower. The Paris scenarios reduce probabilities of extreme warming and increase the probability of limiting global warming to 2°C this century.

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4.2 The TIMES Integrated Assessment Model (TIAM)

4.2.1 Short overview

TIMES 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 a long-term, multiple-period time horizon (Loulou and Labriet, 2007). These energy system operations include the extraction of primary energy such as fossil fuels, the conversion of this primary energy into useful forms (such as electricity, hydrogen, solid heating fuels and liquid transport fuels), and the use of these fuels in a range of energy service applications (vehicular transport, building heating and cooling, and the powering of industrial manufacturing plants). In multi-region versions of the model, fuel trading between regions is also estimated. The TIMES framework is usually applied to the analysis of the entire energy sector, but may also be applied to the detailed study of single sectors (e.g. the electricity and district heat sector). The framework can also be used to simulate the mitigation of non-CO_2 greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O).

The TIMES Integrate Assessment Model, TIAM, is a 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. It uses emissions from these sources to calculate temperature changes using a simple climate module. As such, it can be used to explore a variety of questions on how to mitigate climate change through energy system and transformations, as well as reductions in non-energy CO_2 emissions and non-CO_2 emissions.

4.2.2 Key features of the TIAM model

4.2.2.1 Geographic coverage

The TIAM model covers the entire globe, via fifteen regions, as shown in Table 15:

Table 15: Regional representation and countries included in each region in TIAM

Region ID	Geographic region	Countries
AFR	Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe, and Other Africa
AUS	Australia, New Zealand, Oceania	Australia, New Zealand, Oceania
CAN	Canada	Canada
CHI	China	China
CSA	Central & South America	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and Other Latin America
EEU	Eastern Europe	Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Serbia and Montenegro, Slovenia, Slovakia
IND	India	India
JPN	Japan	Japan

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MEA	Middle East	Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, and Turkey, Cyprus
MEX	Mexico	Mexico
FSU	Russia and Central Asia	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Russian Federation
RKO	Republic of Korea	Republic of Korea
SSEA	(Other) South and Southeast Asia	Bangladesh, Brunei Darussalam, Cambodia, Taiwan (China), Indonesia, DPR of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam and Other Asia
USA	US	US
WEU	Western Europe	Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Norway, Portugal, Spain, Sweden, Switzerland, The Netherlands, UK

4.2.2.2 Energy system detail

TIAM is a technology-rich model; based on the TIMES energy system modelling framework, TIAM features a detailed representation of services and technologies in the energy sector (Figure 8).

4.2.2.3 Multi-year time periods

The time horizon over which TIAM simulates the evolution of the energy system is divided into a user-chosen number of time-periods. In the TIAM version to be used in PARIS REINFORCE, a starting period of 2005 is selected, with further periods including 2006-2007, 2008-2015 (called 2012), and then ten-year periods of 2016-2025 (2020), 2026-2035 (2030), and so on, until 2096-2105 (2100). All years in a given period are considered to be identical. For all quantities such as installed technology levels, power plant capacities and energy and emission flows, any annual input quantity (e.g. coal used in a power plant per year) or output quantity (e.g. electricity generated from the coal plant per year) related to a given time period applies identically to each year in that period.

4.2.2.4 Intra-year time periods (time slices)

In addition to the multi-year time periods described above, in TIAM there are time divisions within a year, called "time slices", which may be defined by the user, so as to capture different weather and energy demand conditions at different times of the year. Currently, there are six time-slices, representing summer daytime, summer night time, winter daytime, winter night time, and "transition season" day time and night time. Time slices are especially important whenever the mode and cost of production of an energy carrier at different times of the year are significantly different (Loulou and Labriet, 2007). For instance, when the demand for electricity fluctuates across the year and a variety of technologies may be chosen for its production at given times of the year (such as wind power when wind resources are high, and solar photovoltaics when there is a high availability of solar radiation). In such cases, the matching of supply and demand requires that the activities of the technologies producing and consuming the electricity be tracked—and matched—in each time slice.

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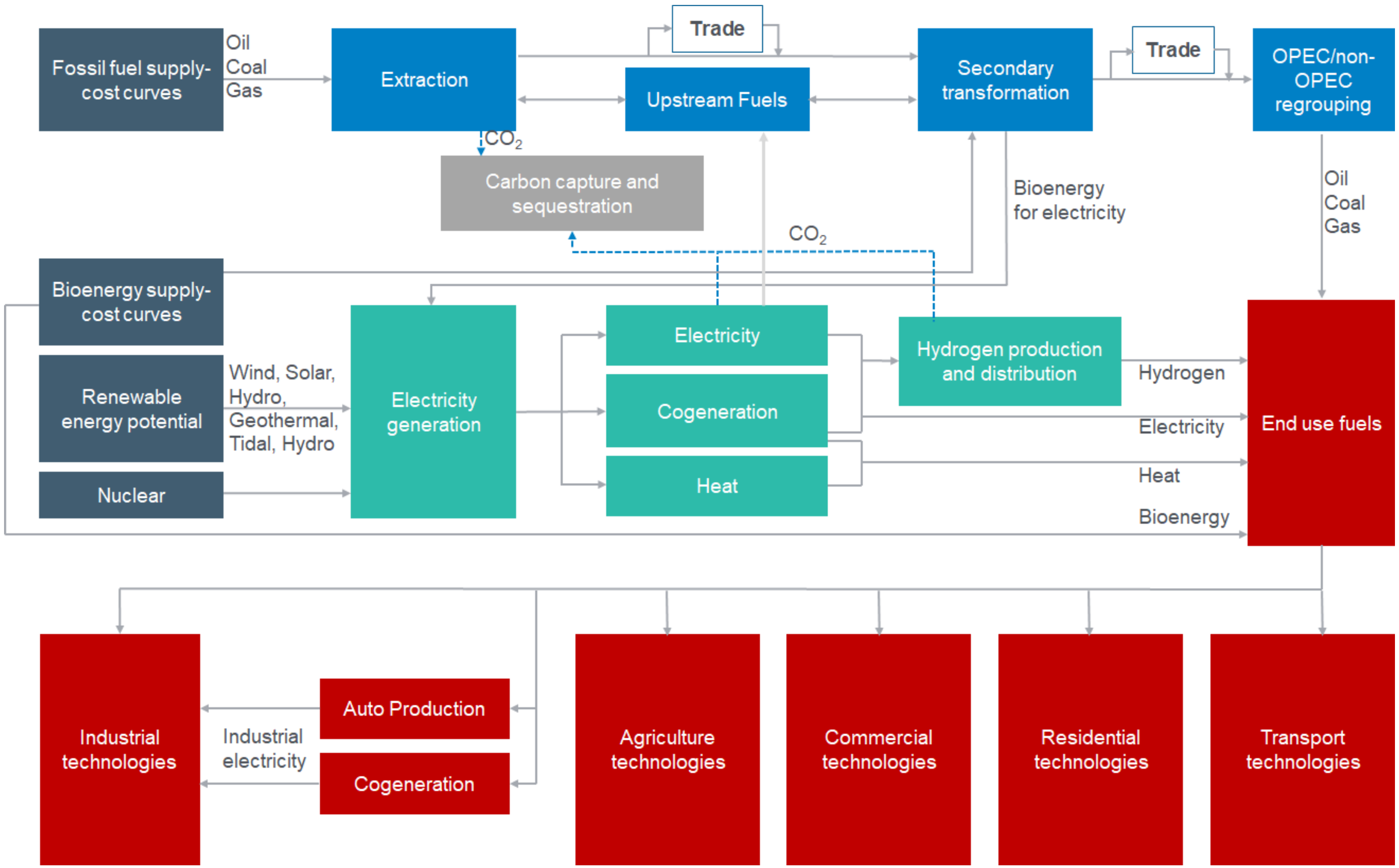

Figure 8: Representation of the TIAM energy system for each region

Source: Authors, based on Loulou and Labriet (2007)

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4.2.3 Climate module & emissions granularity

The climate module in TIAM uses emissions that are calculated within the model, as a result of the energy system's operations, as well as any mitigation of non-energy CO_2 and non-CO_2 gases. The model tracks the three main sources of GHGs—carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20). TIAM's climate module calculates changes in the atmospheric concentration of CO_2, CH_4 and N_2O, and as a consequence the change in atmospheric radiative forcing (which leads to global warming) compared to pre-industrial times, and finally the temperature change over pre-industrial times for the atmosphere and the deep ocean. Figure 9 gives a graphical overview of the module's structure.

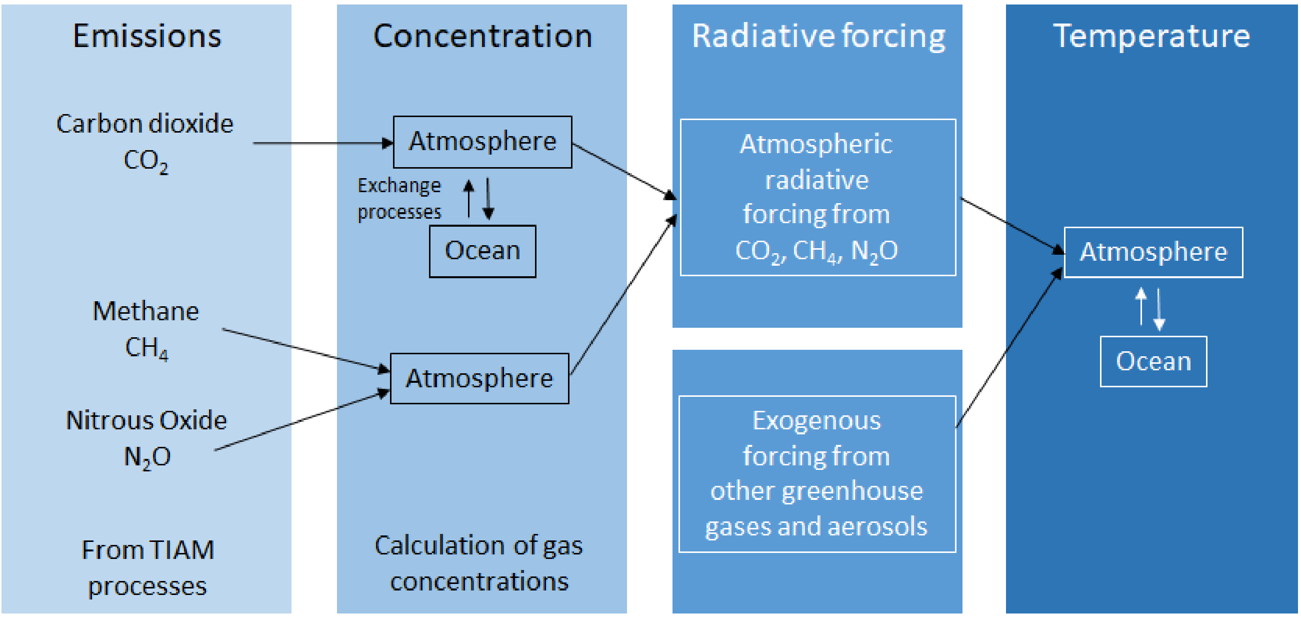

Figure 9: Logic of TIAM climate module

Source: https://iea-etsap.org/TIAM_f/TIAM%20description_slides.pdf

4.2.4 Socioeconomic dimensions

The TIAM model requires inputs concerning the degree to which energy demand, as well as demand for other goods and services which result in GHG emissions (such as agricultural demand) will grow over the course of the 21st century. This is achieved by using various socioeconomic inputs, as described in this section.

4.2.4.1 Economic growth

Economic growth is based on the Shared Socioeconomic Pathways variant 2 (SSP2), sometimes called the "middle-of-the-road" scenario as it generally follows recent past trends in demographic, social, economic and lifestyle developments (Fricko et al., 2017). TIAM specifically uses the OECD projections for SSP2. This results in a growth in world Gross Domestic Product to $540 trn in 2005$ Purchasing Power Parity terms, by 2100, compared to $100 trn in 2020 (Dellink et al., 2017).

4.2.4.2 Population growth

Population growth is also based on SSP2, with global population growing to around 9 billion by 2050 peaking at 9.5 billion in 2060 and dropping back to 9 billion by 2100 (KC and Lutz, 2017). Figure 10 shows the global population and GDP development paths in SSP2.

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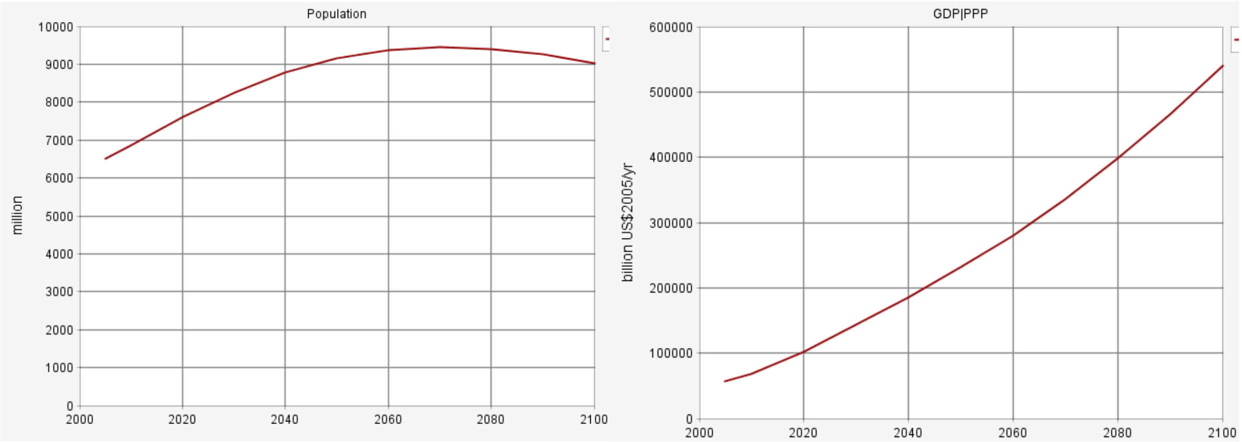

Figure 10: Population and GSP projections for SSP2 in TIAM

Source: https://tntcat.iiasa.ac.at/SspDb

It should be noted that TIAM can be adjusted to use other socioeconomic growth projections apart from SSP2.

4.2.4.3 Sectoral growth

The growth in the industrial, agricultural and retail business sectors in each region is derived from the region's overall GDP growth, with each sector's share of total GDP changing over time. These shares are derived from a historical analysis of how all countries' sectoral shares of output have changed as their overall output grew. Growth of residential households is derived from population growth and assumptions on average household size in each region.

Growth in each of these sectors drives energy demand as described in the next sub-section.

4.2.4.4 Energy demand drivers

The economic, population and sectoral growths are used to determine specific drivers for the growth in energy demands in a "reference" scenario where no climate change mitigation takes place. For example, the demand for the number of billion kilometer-vehicles (bvkm) travelled by automobiles is based on GDP per capita, whereas the growth in the demand for residential space heating is driven by the number of households.

4.2.4.5 Energy demand elasticities

Once the drivers for the different energy demands represented by TIAM are determined and quantified, the construction of the reference demand scenario requires computing a set of energy service demands over the horizon. This is done by choosing elasticities of demands to their respective drivers, in each region, using the following general formula:

Demand = Driver $^{\text{Elasticity}}$

So, for example, the number of billion vehicle km travelled by automobiles, bvkm, grows by a factor which is the growth in the GDP per capita in a region to the power of a pre-defined elasticity:

bvkm = (GDP/capita)$^{\text{Elasticity}}$

In most cases, the elasticities (which vary over time) are less than 1, and decrease over time. For example, an elasticity of 0.8 means that a 10% increase in the growth of GDP per capita in a region would result in an 8% increase in billions of vehicle kilometres driven. Over time this could reduce to a much smaller elasticity, reflecting empirical evidence that demand for energy services such as automobile transport ultimately saturates with rising

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incomes.

TIAM has the capability of estimating the price-based response of these energy service demands to the changing conditions of scenarios in which mitigation occurs. For example, if the cost of energy increases as fossil fuels are replaced by renewables, then the demand for energy services would decrease. To do this, TIAM uses another set of inputs, namely the price elasticities of the demands for each energy service considered. TIAM can then calculate the new demands for these mitigation cases.

4.2.5 Calibration of the model

The TIAM model is calibrated for the initial period (currently 2005) using the International Energy Agency (IEA) world energy statistics for the year 2005, with the projections for energy, installed technology capacity and emissions further calibrated to 2012. This is currently being updated, and the current intention is that, if this update is complete in sufficient time, the version of TIAM to be used in Paris Reinforce will have a full IEA energy statistics-based calibration to the year 2015. The main variables to be calibrated are: the capacities and operating levels of all technologies, the extracted, exported, imported, produced, and consumed quantities for all energy carriers, and the emissions if modelled.

4.2.6 Mitigation/adaptation measures and technologies

TIAM is a technology-rich model that represents most major fossil fuel and low-carbon technologies that are envisaged to be available for at least the first half of the 21st century. By simulating the substitution of low-carbon for high-carbon technologies in response to their relative costs, as well as emissions constraints and/or carbon prices, the TIAM model simulates mitigation. The principal energy sector CO_2 mitigation technology options are as shown in Table 16:

Table 16: Main CO_2 energy system mitigation options in TIAM

Upstream	
Synthetic fuel production	***Hydrogen production***
Gas to liquids with CCS Biomass to liquids (with and without CCS)	Electrolysis Coal to hydrogen with CCS Gas to hydrogen with CCS Biomass to hydrogen with CCS
Electricity and heat	
Electricity generation	***Heat generation***
Coal with CCS Gas with CCS Nuclear (fission and fusion) Hydro Biomass (with and without CCS) Geothermal Solar PV Solar CSP Wind (onshore and offshore) Marine	Biomass
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Hybrid electric vehicles Fully electric vehicles Hydrogen fuel cell vehicles Biofuels in fuel mix Efficiency	Electric Hydrogen Efficiency
Air	***Marine***
Biofuels in fuel mix Hydrogen planes	Gas Hydrogen

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Efficiency	Biofuels Efficiency
Buildings	
Heating	***Lighting***
Gas replacing coal / oil Biofuels Electricity Hydrogen Efficiency	Efficiency
Appliances	***Cooling***
Efficiency	Electricity Efficiency
Industry	
Process heat	***Machine drives***
Gas replacing oil / coal Biomass Hydrogen Electricity	Gas replacing oil / coal Electricity
Steam	***CHP***
Gas replacing oil / coal Electricity	Gas replacing oil / coal Biomass
CCS	***Other***
CCS in iron and steel CCS in cement CCS in chemicals	
Agriculture	
Energy	***Other***
Biomass Electricity	

TIAM also contains a range of non-energy CO_2 and non-CO_2 mitigation options, albeit in a relatively simplified form. For non-energy CO_2, the key option is afforestation. For methane (CH_4), these options are:

- Farm scale digesters for manure.
- Anaerobic digestion, composting, heat production, electricity generation and flaring from landfill methane.
- Minimisation of methane leaks from fossil fuel extraction and distribution, and/or flaring of methane to (lower global warming potential) carbon dioxide gas.

For nitrous oxide (N_2O) these options are:

- Thermal destruction of gas from adipic acid production
- Catalytic reduction of gas from nitric acid production

In addition to the above mitigation options, the TIAM model has recently been developed to simulate the deployment and operation of a range of advanced technologies, including Direct Air Capture for CO_2 removal and sequestration (Realmonte et al., 2019) and even hyper-loop terrestrial high speed transport to substitute for some domestic aviation trips (Napp et al., 2019). In principle many other energy technologies could be simulated in the model.

4.2.7 Economic rationale and model solution

TIAM simultaneously calculates the quantity of production and consumption of the different "commodities" accounted for in the model. These commodities are the different energy forms, the different quantities of deployed technologies, and the different quantities of energy services. The price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. TIAM operates in

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a market-clearing manner, such that prices of commodities are consistent with the supply and demand being in balance for all commodities.

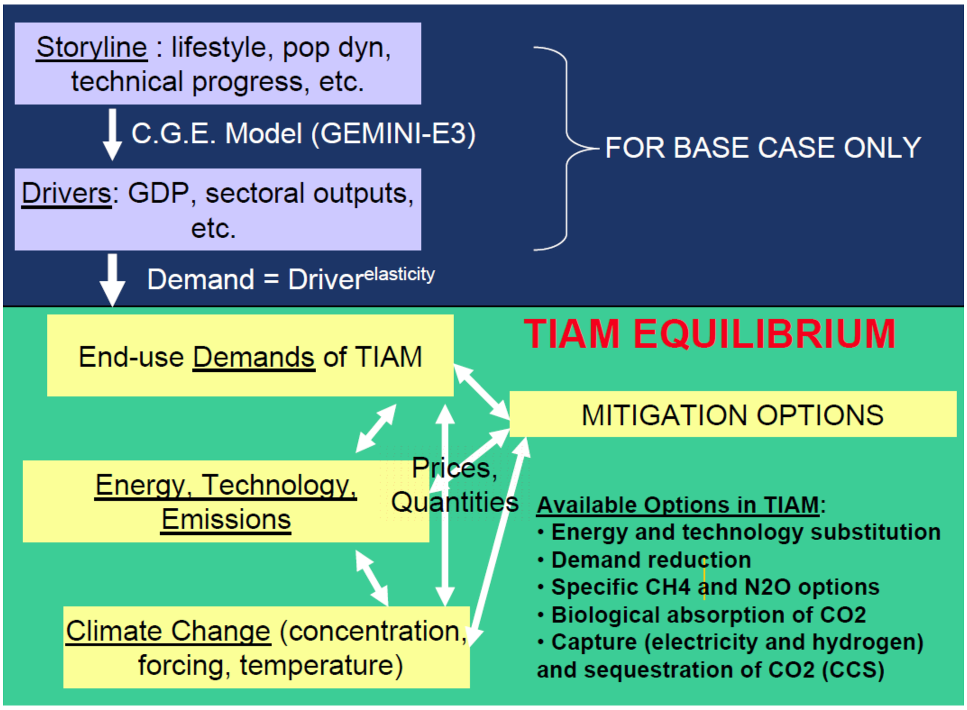

Figure 11: Basic rationale of TIAM equilibrium for commodity supply and demand balance

*Source***:** *https://iea-etsap.org/TIAM_f/TIAM%20description_slides.pdf*

TIAM most commonly operates on a perfect foresight principle, such that it has knowledge of all current and future technology costs and fuel supply curves. This allows it to reach a cost-minimising level of commodity production and consumption, which is consistent with meeting all current and future energy demands, as well as any imposed emissions constraints. The total energy system cost (including any losses to consumers' welfare as a result of energy price rises) is calculated as a Net Present Value (NPV) cost of the energy system over the whole time period until 2100. A "discount" factor of 5% per year is used to value the costs of the energy system at different time points in the future. In other words, a cost of $100 one year in the future would be equated to a cost of $95 today. This discount factor can be changed.

4.2.8 Key parameters

TIAM is a technology-rich tool where techno-economic information is assigned to each process (existing and future) of the system, and therefore many data/parameter values can be extracted and reported.

Key parameters to monitor, discuss and evaluate in the framework of the PARIS REINFORCE project are likely to be:

- Fossil fuel availability and cost (i.e. supply curves) and expected production rates.
- Technology availability and costs.
- Information about under construction/planned/possible energy technologies.
- Regional emissions reduction goals.
- Energy efficiency improvements costs/limits (from the supply side to the demand side).

Parameters can be revised and updated in the framework of the PARIS REINFORCE project, following the feedback of experts (stakeholder engagement), the comparative assessment with other modelling experiences, and the discussion with the partners (modellers).

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4.2.9 Policy questions and SDGs

4.2.9.1 Key policies that can be addressed

TIAM predominantly works by specifying either a carbon price (imposed as a tax) or a carbon emissions constraint in each region that it represents, or alternatively all regions simultaneously. For example, the following further policies can be implemented:

- Minimum / maximum capacity factors on fossil fuel power generation plants (e.g. to simulate minimum or maximum desired levels of operation);
- Subsidies on particular technologies (through adjusting their costs);
- Constraints on the availability of particular technologies (e.g. "no nuclear", variable renewables accounting for no more than 50% of electricity generation);
- Constraints on the growth rates of particular technologies (e.g. carbon capture and storage power generation capacity cannot grow at more than 20% per year)
- Inter-regional emissions trading (or no trading);

This allows TIAM to perform a number of policy-relevant investigations, such as:

- What are the energy system cost and energy technology and fuel mix implications of imposing emissions or climate constraints earlier or later in the century, in different regions at different times and to different levels of stringency?
    - For example, Gambhir et al. (2017) explored the cost implications of introducing delays to mitigation from 2020 to 2030, using the TIAM model and two other integrated assessment models.
- How are the above implications affected with and without emissions permit trading?
    - For example, Gambhir et al. (2014) examined the cost and energy system transformation implications of India meeting a regional emissions reduction target by 2050, with and without international carbon permit trading, whilst Few et al. (2017) considered mitigation costs and feasibility with different shale gas cost and availability assumptions.
- How are the above implications affected with different input assumptions on socioeconomic growth, technological availability, technology costs, fossil fuel costs and availability?
    - For example, Gambhir et al. (2017) examined the mitigation costs of achieving a 2°C climate target with delayed introduction of carbon capture and storage so that it wasn't available before 2050, whilst Realmonte et al. (2019) undertook a deep-dive into the energy system implications of using direct air capture technologies.
- How are the above implications affected by imposed policies such as power plant capacity factor constraints?
    - For example, Napp et al. (2017) considered the feasibility of meeting a 2°C climate target on the assumption that coal plants would need to be kept running at considerable capacity factors for some years to come.

4.2.9.2 Implications for other SDGs

TIAM does not automatically calculate the implications on non-climate SDGs of its least-cost energy system to meet prescribed climate or emissions constraints. However, it is possible to take TIAM's outputs and perform "off-model" calculations to estimate many of the SDG implications. For example, TIAM reports the quantity of fossil fuels combusted in power plants, or of petrol or diesel combusted in vehicles, in each of its reporting years. This in principle would allow an estimation of the air quality implications and subsequent impacts on human health (SDG 3 – good health and wellbeing). Such estimates would have to make assumptions on the spatial distribution of the emissions from such fossil fuel combustion, however. This is something that TIAM, with its purely national and regional, rather than detailed, spatial representation, cannot itself do. The following table provides a summary.

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Table 17: Capacity of the TIAM model to address non-climate SDGs

SDG	Details
§3. Health (e.g., air-pollution related mortality)	The use of solid fuels in buildings can form the basis of local air pollution calculations.
§7. Affordable and clean energy	Cost-effectiveness and availability of low-carbon energy is a central set of TIAM outputs.
§8. Decent work & economic growth	TIAM reports energy system costs under different scenarios, often expressed as a share of GDP, giving a measure of economic losses due to mitigation. Note, this does not account for economic gains due to mitigation that result from lower temperature changes.
§15: Life on land	Afforestation measures can be taken into account; RES potential/exploitation and investment decisions (e.g. energy infrastructures) can be subject to land-specific constraints (natural and regulatory).

4.2.10 Recent use cases

Table 18: List of recent publications using the TIAM model

Paper	Topic	Key findings
Realmonte et al. (2019)	An investigation of the role of Direct Air Capture (DAC) in meeting global 1.5°C and 2°C pathways	DAC can reduce the policy costs of mitigation in the near-term, but there are many uncertainties about its scale-up potential and, if we ease mitigation efforts and rely on DAC, even if it does not deliver large-scale removals, we will overshoot the Paris climate goals.
Napp et al. (2019)	Analysis of deep mitigation pathways with advanced mitigation technologies including hydrogen aviation, hydrogen in industrial manufacturing, and CCS across industry, and deep demand side reductions including modal shifts and other behaviour changes	Development and deployment of a range of advanced demand-side technologies, combined with demand-side energy savings as a result of behaviour change, could significantly ease the pressure on using negative emissions like bio-energy with carbon capture to meet the Paris goals.
Gambhir et al. (2017)	Establishing a set of metrics by which to assess the feasibility of achieving different climate targets	Using multiple metrics such as mitigation cost, carbon price, degree of asset stranding, quantity of negative emissions required and rates of energy efficiency improvement, it is significantly (>30%) cheaper and much more feasible to meet a 2°C target by starting globally coordinated mitigation action in 2020 compared to 2030.
Gambhir et al. (2017)	Analysis coupled with a separate non-CO_2 and separate climate model to assess the contribution that non-CO_2 mitigation can make to reaching deep mitigation targets	Attempting to meet any climate target without actively mitigating non-CO_2 greenhouse gases would be much more expensive than using a multi-gas mitigation strategy.

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Napp et al. (2017)	Analysis of the potential to meet deep mitigation targets with a variety of growth and other constraints on technology deployment, so that future technology transition rates do not exceed the fastest historical rates	If we cannot exceed historical patterns and rates of energy system transformation, then we will miss the 2ºC target by about 0.1ºC. Thus, we must implement policies to accelerate the transition beyond past rates.
Few et al., (2017)	Analysis of the costs of meeting 2ºC climate targets with different assumptions on the cost and availability of shale gas in different world regions.	Exploitation of shale gas could make mitigation to 2ºC marginally more expensive, but could also lead to some temperature target overshoot if fugitive methane emissions are not effectively regulated.
Chiodi et al. (2016)	Analysis of the medium- and long-term implications of increased development of unconventional gas and oil and their by-products on European market	Although in Europe natural gas can be considered as transition fuel towards a low-carbon economy, the natural gas market will expand in the future years and will contribute—replacing other more carbon intensive fossil fuels—to the decarbonisation of energy sectors. The EU-28 exploitation of unconventional oil will be very limited.

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4.3 The ModUlar energy system Simulation Environment (MUSE)

4.3.1 Short overview

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

MUSE is an agent-based framework, in that it explicitly characterises the decision-making process of firms and consumers in the energy system, thereby capturing a variety of features of market imperfection. MUSE is also technology-rich, in that it characterises the cost and performance of each technology option, tracks technology stock, and provides details on investment, operating costs, energy consumption, and emissions with a detailed bottom-up perspective.

The agent-based modular structure of the sectors is brought together in a partial equilibrium on the energy system through a market clearing algorithm, which balances supply and demand of each energy commodity. The market clearing algorithm is also able to enforce a carbon budget, which escalates a carbon price until agents in all sectors respond and emissions constraints are met.

MUSE-Global is an implementation of a global model in the MUSE framework, characterising 28-regions of the world, and running over a time horizon of 2010 to 2100. It can be used to explore a variety of questions on how to mitigate climate change given realistic constraints and frictions on system change, and has been applied to show that slightly sub-optimal transition pathways may be more likely to succeed than optimal ones.

4.3.2 Key features of the MUSE model

4.3.2.1 Geographic coverage

The MUSE-Global model covers the entire world, via twenty-eight regions, as shown in Table 19:

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Table 19: Regional representation and countries included in each region in MUSE-Global

Geographic region	Countries
AE	Switzerland, Turkey
ASEAN	Brunei, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, Vietnam
ATE	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
AUS	Australia, New Zealand
BRA	Brazil
CAN	Canada
CHL	Chile
CHN	China, Hong Kong, Taiwan
DNK	Denmark
EA	Afghanistan, Bangladesh, Bhutan, Chinese Taipei, Cook Islands, Dem. Rep. Korea, East Timor, Fiji, French Polynesia, Kiribati, Macau, Maldives, Mongolia, Nepal, New Caledonia, Pakistan, Papua New Guinea, Samoa, Solomon Islands, Sri Lanka, Tonga, Vanuatu
ELA	Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, British Virgin Islands, Cayman Islands, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guyana, Grenada, Grenadines, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Lucia, Saint Pierre et Miquelon, St. Kitts and Nevis, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela
EU7	Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta, N. Cyprus, Romania
EU18	Austria, Belgium, Czech Republic, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, United Kingdom
FIN	Finland
IND	India
ISL	Iceland
ISR	Israel
JPN	Japan
KOR	South Korea
MEA	Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, Other Middle East
MEX	Mexico
NCA	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Dem. Rep. Congo, Djibouti, Egypt, Eq. Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe, Other Africa
NOR	Norway
OETE	Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Kosovo, North Macedonia, Moldova, Montenegro, Serbia, Ukraine
RUS	Russia
SWE	Sweden
USA	United States of America
ZAF	South Africa

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4.3.2.2 Energy sectoral detail

As described above, MUSE characterises agent-based decision making in each sector of the economy. The sector breakdown is shown in Figure 12:

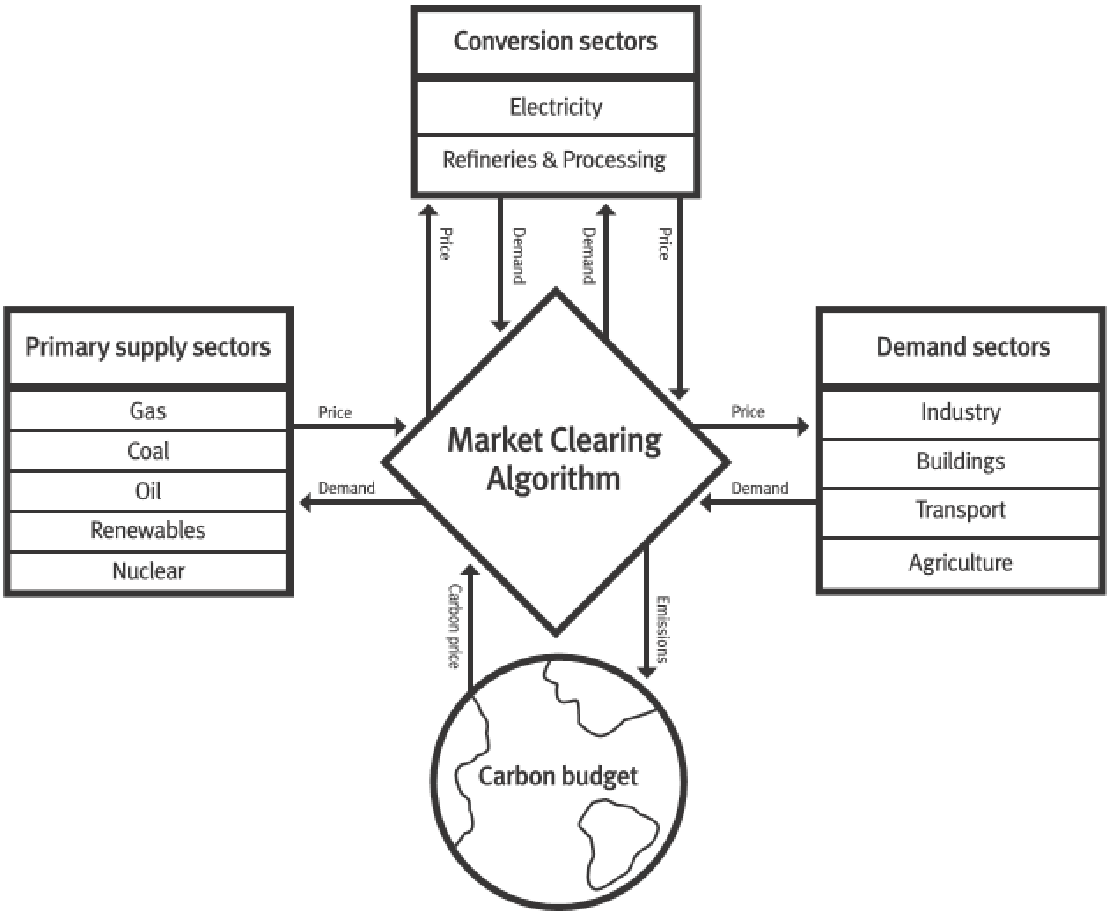

Figure 12: Representation of the MUSE energy sectors and clearing function

4.3.2.3 Multi-year time periods

The time horizon over which MUSE simulates the evolution of the energy system is divided into a user-chosen number of time periods. In MUSE-Global, to be used in PARIS REINFORCE, there is a starting period of 2010, with further years divided in ten-year periods up to 2100. All years in a given period are considered identical.

4.3.2.4 Intra-year time periods (time slices)

In addition to the multi-year time periods described above, in MUSE there are time divisions within a year, called “time slices”, which may be defined by the user, so as to capture different resource supply, weather and energy demand conditions at different times of the year. This is the case for instance when the demand for an electricity fluctuates across the year and a variety of technologies may be chosen for its production at given times of the year (such as wind power when wind resources are high, and solar photovoltaics when there is a high availability of solar radiation).

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4.3.3 Emissions granularity

As described above, the achievement of climate change targets in MUSE-Global is dealt with via the imposition of emissions limits on each time period. The model tracks the three main sources of GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20). These gases are tracked for each technology, sector, region, and for the world, in each time period.

4.3.4 Socioeconomic dimensions

4.3.4.1 Economic growth

Economic growth is based on the 2nd Shared Socioeconomic Pathway (SSP2), sometimes called the "middle-of-the-road" scenario, as it generally continues recent past trends in demographic, social, economic and lifestyle developments (Fricko et al., 2017) (Figure 13).

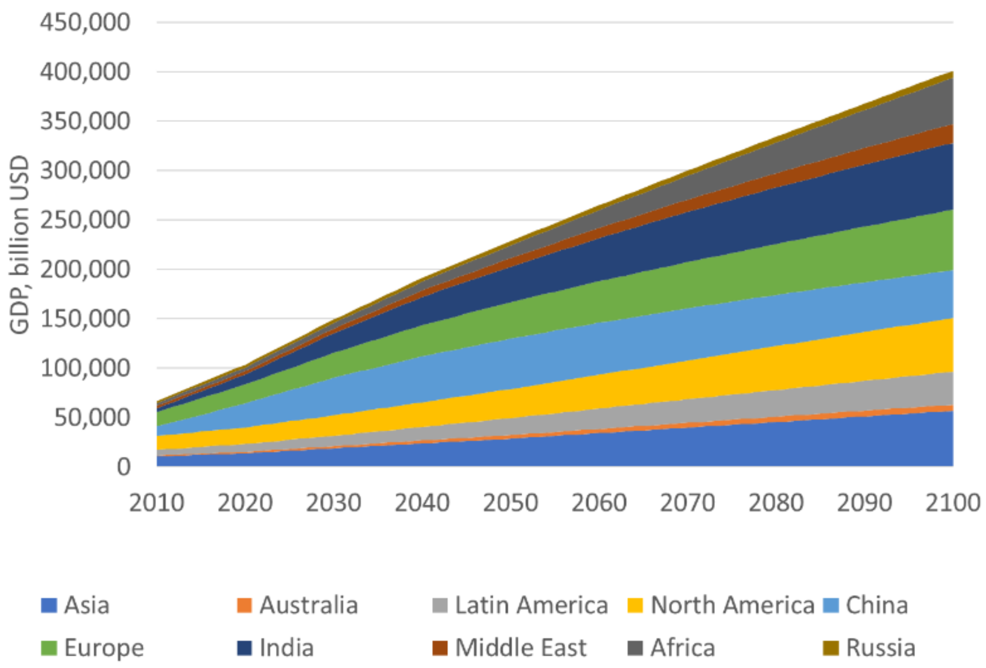

Figure 13: GDP projections in MUSE

4.3.4.2 Population growth

Population growth is also based on SSP2, with global population peaking to around 9.5 billion by 2050 and dropping back to 9 billion by 2100, as shown in Figure 14.

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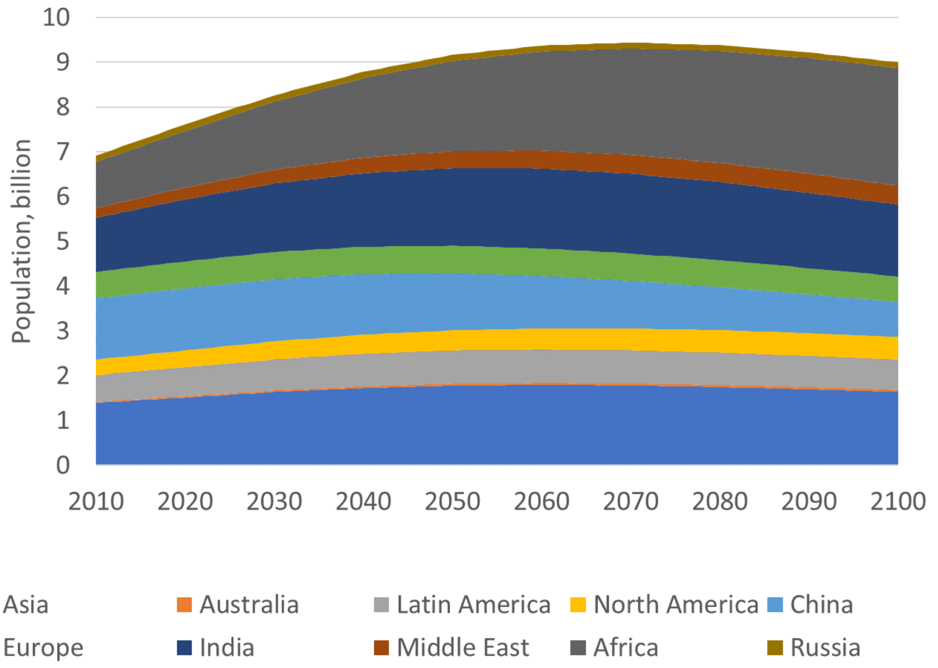

Figure 14: Population projections in MUSE

4.3.4.3 Sectoral growth

The growth in the industrial, agricultural and retail business sectors in each region is derived from the region's overall GDP growth, with regression applied to determine historical relationships, and the best fit matches for each service demand category being applied to project growth forwards. With reference to the agricultural sector, the historical trend of service demands (crop and meat demands between 1970 and 2015) are regressed against the exogenously given macroeconomic drivers (GDP and population) (Figure 15, from Kerdan et al., 2019d).

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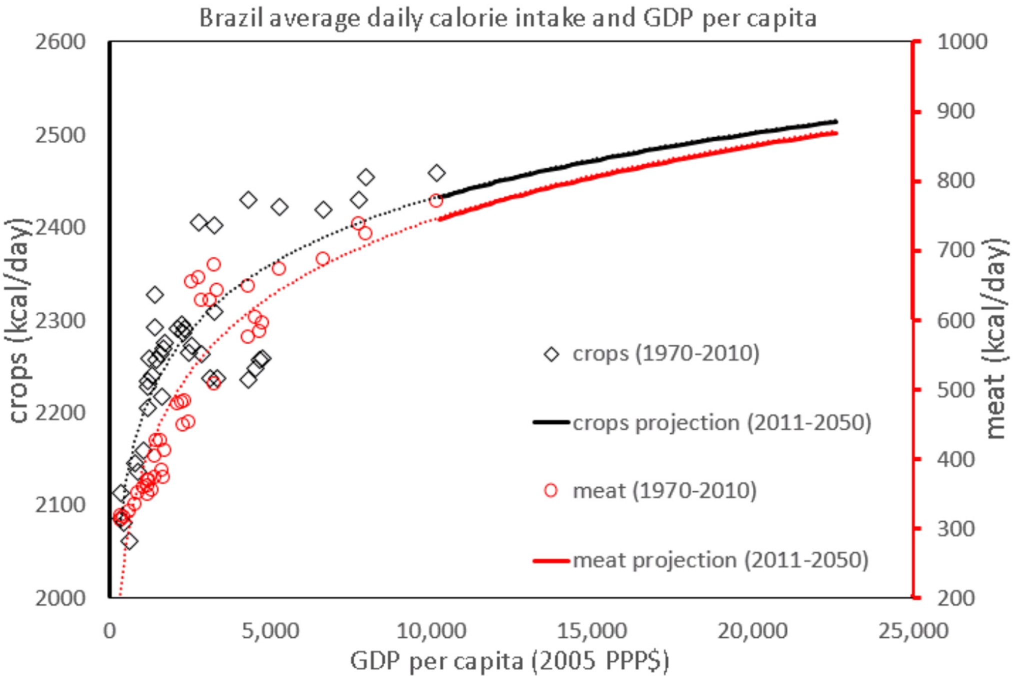

Figure 15: Example of service demand regression over historical macroeconomic drivers in MUSE

Source: Kerdan et al., 2019d

4.3.4.4 Energy demand drivers

The economic, population and sectoral growths are used to determine specific drivers for the growth in energy demands in a "reference" scenario in which there is no climate change mitigation. For example, in the agricultural sector, demand for one of the services is linked to demand for food. Being highly correlated with income and population growth, the regression model used in MUSE is represented in the following equation, because of the best fit with historical demand of food:

$$\boldsymbol{log\ C = a + b \cdot ln\ (GDPpc)}$$

where *C* represents the consumption of food per capita and GDPpc is the region GDP divided over the population.

4.3.4.5 Energy demand elasticities

MUSE does not include endogenous own-price elasticity. Instead, demand changes may be modelled via sensitivity analysis.

4.3.4.6 Other socioeconomic dimensions

As described above, MUSE uses an agent-based formulation to determine possible pathways of energy system transition. As such, socioeconomic categorisation of populations of investors and/or consumers is used to capture heterogeneity in investment decision making. The technique relies upon survey data, and widely available socioeconomic metrics, e.g. from the World Bank to achieve this. For example, in the building sector the SINUS-Milieus Typology (Sinus Sociovision, 2017) was used for the classification and attributes assignment of agents. According to the methodology introduced above, socioeconomic survey data of household representative persons can be adopted to allocate households into social groups.

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4.3.5 Calibration of the model

The MUSE model is calibrated for the initial period (2010) using IEA world energy statistics for the year 2010, with the projections for energy, installed technology capacity and emissions further calibrated to 2015. The main variables to be calibrated are the capacities and operating levels of all technologies present in the world in 2010; the extracted, exported, imported, produced, and consumed quantities for all energy carriers; and the emissions.

4.3.6 Mitigation/adaptation measures and technologies

MUSE is a technology-rich model that represents most major fossil fuel and low-carbon technologies that are envisaged to be available for at least the first half of the 21st century. As described above, the calibration process determines what technologies existed in the global energy system in the base year. The principal energy sector CO_2 mitigation technology options are as shown in Table 20:

Table 20: Main CO_2 energy system mitigation options in MUSE

Upstream	
Synthetic fuel production	***Hydrogen production***
Coal to gas with CCS Coal to liquids with CCS Gas to liquids with CCS Biomass to liquids (with and without CCS)	Electrolysis Coal to hydrogen with CCS Gas to hydrogen with CCS Biomass to hydrogen with CCS
Electricity	
Electricity generation	***Electricity generation from variable renewables***
Coal with CCS Gas with CCS Nuclear (fission) Hydro (small and large) Biomass (with and without CCS) Geothermal Storage	Solar PV (ground and rooftop) Concentrated solar power Wind (onshore and offshore) Tidal
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Hybrid/Plugin hybrid electric vehicles (using mixtures of biofuels) Fully electric vehicles Hydrogen fuel cell vehicles Hybrid/Plugin hybrid hydrogen fuel cell vehicles Liquid hydrogen vehicles Flexible vehicles (using biofuel mixtures)	Electric Hydrogen
Air	***Shipping***
Biofuels in fuel mix Hybrid electric planes Hybrid electric planes using biofuels	Gas/LNG Hydrogen Biofuels
Buildings	
Heating	***Lighting and appliances***
Gas (replacing coal/oil)/biomass/electricity/hydrogen boiler Gas/biomass/electricity/hydrogen boilers integrated with solar thermal systems Gas/biomass co-generation (CHP and micro CHP) District heating (gas, biomass, waste heat) standalone or integrated with thermal systems and heat pumps Efficiency	Efficiency LED lighting systems
Cooking	***Cooling***
Biomass Electricity Hydrogen	Heat pumps Heat pumps integrated with solar thermal Efficient air conditioning systems
Industry	
Iron/steel, pulp/paper, chemicals, aluminum, cement industries	***CCS***
Gas replacing oil / coal Biomass	CCS in iron and steel (with/o bioenergy) CCS in cement (with/o bioenergy)

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Biomethane Electrolysis (for ammonia production) Efficiency	CCS in chemicals (with/o bioenergy) CCS in pulp and paper (with/o bioenergy) CCS in aluminum (with/o bioenergy)
Agriculture	
Energy	***non CO_2 emissions***
Gas replacing fuel oil Biomass Electricity Mechanisation	Mechanisation

4.3.7 Economic rationale and model solution

MUSE simulates a microeconomic equilibrium on the energy system. It consists of modular independent agent-based sector modules, joined together by a market clearing algorithm, as shown in Figure 12.

The market clearing algorithm iterates across all of the sector modules, interchanging price and quantity of each energy commodity in each region, until an equilibrium is reached. It sends commodity prices to the end-use sectors and receives back demand for each of these commodities. It sums up these demands and sends them to the conversion and/or supply sectors, which in turn send back a price. This is used to inform an updated price in the market clearing algorithm, whence the procedure iterates again (i.e. updated prices are sent to the end-use sectors, etc.). Eventually this process results in a microeconomic equilibrium for each energy commodity in each region. When investigating climate change mitigation, a carbon budget is imposed on each time period. A GHG emissions price is then set in the market clearing algorithm such that the carbon budget is achieved (i.e. by pricing emissions, and thereby incentivising investment in low emissions technology in all sectors via the agent-based modelling described below).

Each agent-based sector module in MUSE is modelled in a way that is appropriate for that sector (i.e. MUSE is a hybrid modular approach). As such, MUSE developers are able to characterise investment decision making in different ways in each sector, to capture the features that are the most important and therefore produce a more realistic representation of energy system transitions. MUSE uses socioeconomic and firm-level data and analyses to characterise a set of investment decision makers (agents) for each sector. Each sector then applies an agent-based modelling (ABM) approach where "agents" (firms or consumers) apply rules to (a) determine which technologies will be considered for investment; (b) calculate a set of objectives according to their decision making preferences; and (c) use a method to combine these objectives to make a final investment decision. Each of these steps is bespoke, where developers can choose from a set of pre-defined rules or can code and add their own objectives and decision rules.

As such, overall MUSE is a limited-foresight model that strives to represent the frictions and challenges that could occur as the world aims for systemic technology change to achieve climate change mitigation over the coming eight decades. Data paucity, technology cost and performance uncertainty, and spatial and temporal coarseness are all weaknesses of this approach, as they are with any other form of integrated assessment modelling.

4.3.8 Key parameters

The MUSE model requires inputs concerning the degree to which energy demand, as well as demand for other goods and services which result in GHG emissions (such as agricultural demand), will change over the time horizon. Future demand projections of each service in each region are based on societal input variables, i.e. population and GDP.

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4.3.9 Policy questions and SDGs

4.3.9.1 Key policies that can be addressed

MUSE is usually applied by specifying either a carbon tax or a carbon emissions constraint for the world as a whole. This acts as a proxy for all other climate-related policies. However, a further range of policy levers are possible to implement in MUSE, as follows:

- Capacity factor limits on fossil fuel power generation plants (e.g. to simulate minimum or maximum desired levels of operation)
- Subsidies on particular technologies (through adjusting their costs)
- Constraints on the availability of particular technologies (e.g. "no nuclear", variable renewables accounting for no more than 50% of electricity generation, etc.)
- Constraints on the growth rates of particular technologies (e.g. CCS power generation capacity cannot grow at more than 20% per year), addition of capacity (e.g. cannot grow more than 5 GW per year, and cumulative capacity limits (e.g. cannot exceed 60 GW in total, ever).

4.3.9.2 Implications for other SDGs

MUSE does not calculate non-climate SDGs. However, it is possible to take MUSE's outputs and perform "off-model" calculations to estimate many of the SDG implications. For example, MUSE reports the quantity of offshore wind power plants in each of its reporting years. This allows an estimation of the employment that such activity would generate in the region. Furthermore, MUSE may be coupled with macroeconomic and/or lifecycle assessment tools in order to calculate SDG-relevant quantities; for example, impact on income distribution, impact on air or water quality, etc.

4.3.10 Recent use cases

Table 21: List of recent publications using the MUSE model

Paper	Topic	Key findings
Kerdan et al. (2019a)	Assessing gas infrastructure pathways for the southern states of Brazil	Results suggest that, due to the expected increase in regional gas demand in South Brazil, the existing gas infrastructure would require additional investments. Depending on the renegotiation outcomes between Brazil and Bolivia (i.e. either maintaining constant, halving, or halting the Bolivian import of gas), natural gas demand could be covered by a share of alternative supply options, such as an increase in pre-salt production, LNG imports and imports from a new Argentinian pipeline.
Kerdan et al. (2019b)	Exploring the complex relationship between sugarcane production, deforestation and fossil fuel resource exploitation under two 2°C scenarios for Brazil obtained by either limiting the natural gas or the bioenergy supply	Results suggest that that the promotion of bioenergy in Brazil, should be accompanied by strong policies on limiting deforestation which still represents an important source of emissions. On the other hand, emissions from natural gas can be compensated by the capture and sequestration potential of the Brazilian forests as the natural gas supply helps lowering the deforestation rates. In this context where bioenergy supply reduces, new investments would be necessary to boost the

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		existing gas infrastructure capacity.
Kerdan et al. (2019c)	An analysis focused on carbon sequestration in Brazil comparing reforestation and sugarcane expansion on abandoned agricultural lands	The results suggest that should Brazil enforce policies on promoting reforestation, it would have the potential to become a large GHG abatement region thanks due to its high carbon (C) sequestration rates. Brazil is expected to liberate up to 68.4 Mha of agricultural land by 2050. If this land is abandoned, the country carbon stock could be reduced from 135.9 PgC in 2010 to 129.9 PgC. If a sugarcane expansion policy is followed, by mid-century the carbon stock could reach 134.2 PgC, whereas if a reforestation policy is implemented it could reach 139.2 PgC.
Kerdan et al. (2019d)	An analysis exploring the role of land use and reforestation in achieving carbon mitigation targets in Brazil	The model tracks agricultural technology diffusion, energy use, agrochemical demands and its implication on land use and energy and non-energy emissions. Results show the importance of reforestation as a significant contributor to carbon sequestration. Brazil has the potential to sequester around 5.6 Gt CO_2 by 2050 through reforestation. In this scenario, the capital investment in carbon sequestration and storage would be substantially reduced.
Sachs et al. (2019a)	Capturing many of the characteristics of the consumers' behaviour affecting investment decisions	The paper sets out the MUSE agent-based method for modelling of the investment decision making processes of heterogeneous decision makers in the energy system. The integration of several decision-making steps including information gathering, the assessment of the performance of each option as well as the final selection enables a more flexible and realistic representation of the energy system change compared to the majority of the energy systems models. The agent-based method leads to a range of technologies in the market during a transition phase, continuous investment in low capital cost technologies, and eventually the emergence of a low carbon system based on new mass market technologies.
Sachs et al. (2019b)	Spatially- and temporally-resolved estimation of global space heating, space cooling and hot water demand	The result is the first self-consistent analysis of three energy end-uses (global space heating, space cooling, and hot water demand) at a global scale, disaggregated into country and energy density categories, and provided in profile form to capture seasonal and diurnal demand variations. Global space heating demand reflect not only population and temperature characteristics but also the correlation of gross domestic product with the ownership of air conditioning equipment. In terms of energy density, the results show that a relatively small portion of demand (approx. ~ 5%) occurs at very high

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		energy density locations (i.e. above 36.9 GW h/km2), while ~50% of demand occurs in low energy density locations (i.e. below 1.79 GW h/km2).
Crow et al. (2018)	Modelling dynamic supply curves	The paper presents how dynamic upstream gas supply curves are modelled using a global, bottom-up model of the natural gas supply. In contrast to most "static" supply-side models, which bracket resources by average cost, the MUSE upstream gas model creates a range of dynamic outputs by simulating investment and operating decisions in the upstream gas industry triggered in response to forward price and/or demand signals.

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4.4 The 42 model

4.4.1 Short overview

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

4.4.2 Key features of the 42 model

4.4.2.1 Geographic coverage

In the 42 model, the world is divided into 50 countries and regions, as shown in Table 22:

Table 22: Countries/Regions under consideration in the 42 model

Regions	Geographic regions/countries covered in the model
North America	USA, Canada, Mexico
Central and South America	Argentina, Brazil, Columbia, Ecuador, Venezuela, Other Central and South America
Europe	EU, Norway, Iceland, Switzerland, Turkey, Other Europe
Commonwealth of Independent States	Russia, Azerbaijan, Belarus, Kazakhstan, Turkmenistan, Ukraine, Uzbekistan, Other countries
Africa	Angola, Algeria, Egypt, Gabon, Libya, Mozambique, Nigeria, South Africa, Other Africa
Middle East	United Arab Emirates, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, Other Middle East
Asia	Australia, China, India, Indonesia, Japan, South Korea, Malaysia, New Zeeland, Thailand, Vietnam, Other Asia

4.4.2.2 Energy sectoral detail

The description of the energy sector is performed through energy balances synchronised with the IEA methodology and built on the basis of its data.

Primary energy resources include coal, natural gas, oil, nuclear, hydro, solar, wind, biofuels, and other renewables; while secondary energy resources include electricity, heat, oil products (gasoline, diesel, fuel oil, jet fuel, naphtha and LPG, and others).

The structure of the energy consumption balance is quite typical, although there is particular aggregation in the final consumption unit. The model also distinguishes energy consumption for bunkering. Road transport is divided into cars and trucks.

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Table 23: Energy transformation and demand sectors in the 42 model

Transformation	Final Consumption	Total Primary Energy Supply
Power sector	Industry	Bunkers
Heating	Aviation	
Oil refineries	Road transport (cars and trucks)	
Coal transformation	Rail transport	
Gas works	Other transport	
Liquefaction	Residential	
Other transformation	Commercial and public services	
Loses, Energy industry own use	Non-energy use in chemical	
	Other non-energy use	

4.4.2.3 Time coverage

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

4.4.3 Emissions granularity

42 does not have a climate module and does not calculate the impact of anthropogenic emissions on climate change. The current version of the model tracks only carbon dioxide (CO_2) emissions. It may be expanded during the implementation of the PARIS REINFORCE project, in order to provide a more complete description of anthropogenic emissions.

4.4.4 Socioeconomic dimensions

42 requires a number of socioeconomic metrics, according to which both energy consumption and energy-related CO_2 emissions are modelled. The key parameters concern economic growth and its structure, population, vehicle fleet and energy intensity for each country/region under consideration. The current version of the 42 model contains relevant and representative data for all of these dimensions.

4.4.4.1 Population growth

Population growth is one of the primary causes of world energy consumption increase. The UN demographic forecast is usually employed as a basis for population scenarios. The reference (medium) scenario assumes an increase in the global population to 9.5 billion by 2045 (average annual growth rate of 0.7%). 42 does not consider population structure (e.g. by age group, urbanisation status, etc.).

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4.4.4.2 Economic growth

Another driver for increasing energy consumption is economic growth. Currently, scenario hypotheses on the GDP growth rates for all the countries and regions under consideration are set in accordance with calculations on economic forecasting models performed by the team of the Institute of Economic Forecasting of the Russian Academy of Sciences. According to these estimates, global GDP will increase 2.45 times, from 110 (currently) to 270 trillion dollars (2011 PPP) by 2045. However, 42 can use any hypotheses on GDP growth as inputs.

The structure of GDP is also an important metric, since different sectors are characterised by various levels of energy intensity. The 42 model distinguishes the following components of the total value added in the economy of all countries/regions: material production, transport, and services. The ratio of these segments is analysed basing on an econometric approach.

4.4.4.3 Vehicle fleet

Road transport is an important energy consumer, providing about 40% of global oil demand. The vehicle fleet size reflects the economic situation: the growth of household income stimulates the purchase of a private vehicle, and economic development creates a cargo flow for transportation. Further development of the world economy is associated with an increase of the fleet size. The reference scenario for the car fleet in Russia is defined as population times the automobilisation rate. At the same time, the automobilisation rate depends on GDP per capita (the relationship between these parameters is described by an S-shaped curve, which is similar to consumer demand saturation). However, its future dynamics can be significantly transformed. The modern generation of young people is less interested in buying a personal car, and new technologies make a sharing-based model of transportation affordable and convenient. The development of online services and remote work can also reduce the demand for mobility. Given these factors, transportation and fleet forecasts vary widely.

Nowadays, the most crucial trend is government incentives to change the structure of the automotive market in the direction of low-carbon solutions (electric vehicles). Therefore, structural shifts in the fleet constitute another key socioeconomic metric for future energy consumption. Simulating the growth of the share of low-carbon transport is a way of modelling climate change mitigation.

4.4.4.4 Energy intensity of the economy

Economic and demographic development provide gross characteristics of energy demand. However, energy efficiency is superimposed on these, slowing the increase of global consumption and CO_2 emissions. In the 42 model, there is no relationship between the investment process and energy efficiency. Instead, energy intensities of different industries are inputs to the model.

The logarithmic approximation is used as typical dynamics of energy intensity curves in different industries. It is characterised by damping dynamics and is well suited to describe the logic of energy consumption process evolution. The growing logarithmic curve produces a situation of increasing consumption, as it implies that the role of an energy resource is strengthened in a specific economic sector (for instance, electrification of residences and services; increase in electric equipment in industries of developing countries; spread of carbon-free resources in developed countries). The falling logarithmic curve produces situations either of improving the efficiency or of consumers moving away from a particular energy source (for instance, a replacement of coal).

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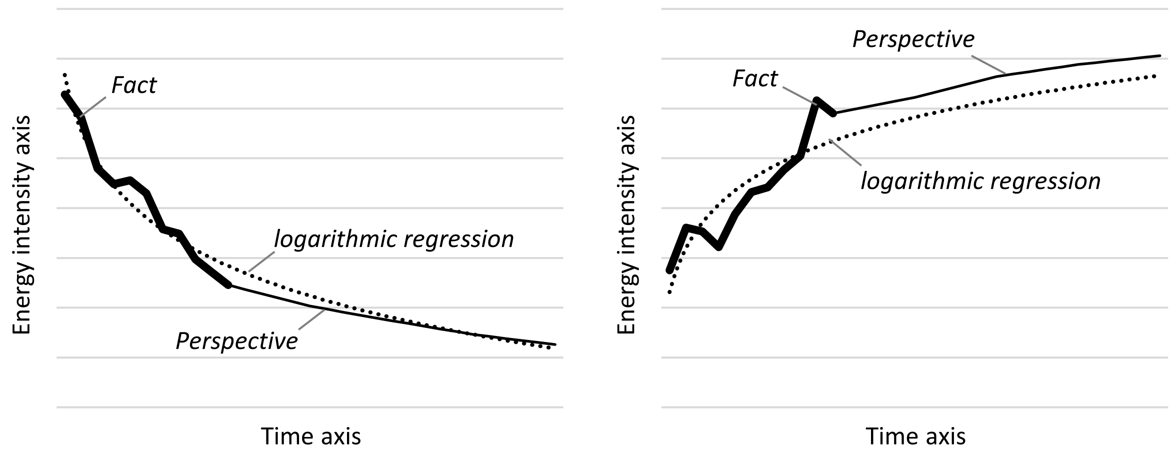

Figure 16: Typical dynamics of energy intensity curves in the 42 Model

4.4.5 Calibration of the model

The 42 model is calibrated to IEA's energy balances for the period of 1990-2016, for each of the countries/regions considered.

4.4.6 Mitigation/adaptation measures and technologies

42 is a simulation model focused on the implementation of low-carbon solutions in the field of electricity and heat production, and automobile transport. By simulating the substitution of low-carbon for high-carbon technologies, the 42 model simulates mitigation. The principal energy-sector CO_2 mitigation technology options are as shown in Table 24. Particular attention is paid to improving the efficiency of energy consumption through the simulation of energy intensity curves.

Table 24: Main CO_2 energy system mitigation options in the 42 model

Electricity generation	***Heat generation***
Efficiency Nuclear Hydro Biomass Solar Wind	Efficiency Geothermal Biomass
Road transport	***Other transport***
Efficiency Gas vehicles Electric vehicles	Gas Electric Efficiency
Industry	***Residential***
Gas replacing oil / coal Electricity Biomass Efficiency	Efficiency Electrification Gasification

4.4.7 Economic rationale and model solution

Modelling is based on a bottom-up approach: first, the final consumption of energy resources is estimated for industry, transport, the residential sector, and services; and then the model calculates the necessary amount of primary energy resources needed to produce petroleum products, electricity and heat. The amount of primary

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energy consumption in these two phases explains the total energy consumption, which is multiplied by the carbon intensity vector and thus CO_2 emissions associated with the energy sector are calculated.

The process of energy consumption is modelled as a combination of three classes of influencing factors:

Consumption = Gross factor * Structural factor * Technological factor

Gross factor characterises the size of an object consuming energy. The examples of such factors distinguished are as follows:

- GDP (gross factor for the entire economy)
- population (gross factor for residential sector)
- vehicle fleet (gross factor of transport sector)
- electricity production (gross factor of power sector)

The structural factor is necessary in order to identify which part of the "gross" object consumes a particular energy product. The following structural factors are distinguished:

- GDP structure (shares of value added in material production, transport and services in relation to GDP)
- electricity production structure (it determines how much electricity will be generated on the basis of different types of energy resources)
- vehicle fleet structure (it shows how many cars will consume different types of motor fuels)

The technological factor is necessary in order to describe the dynamics of specific energy consumption. For example, how much natural gas is needed to produce 1 kWh of electricity; how many litres of diesel are needed to drive 100 km by car; how much energy is needed to create 1 million USD of value added in the services. The following technological factors are distinguished:

- vehicle fuel efficiency per 100 km
- efficiencies of power generation technologies
- energy intensity of value added in different sectors

Using all these key drivers of future energy demand as model inputs, the 42 is focused on energy-associated CO_2 emissions calculation according to a simulation-based approach.

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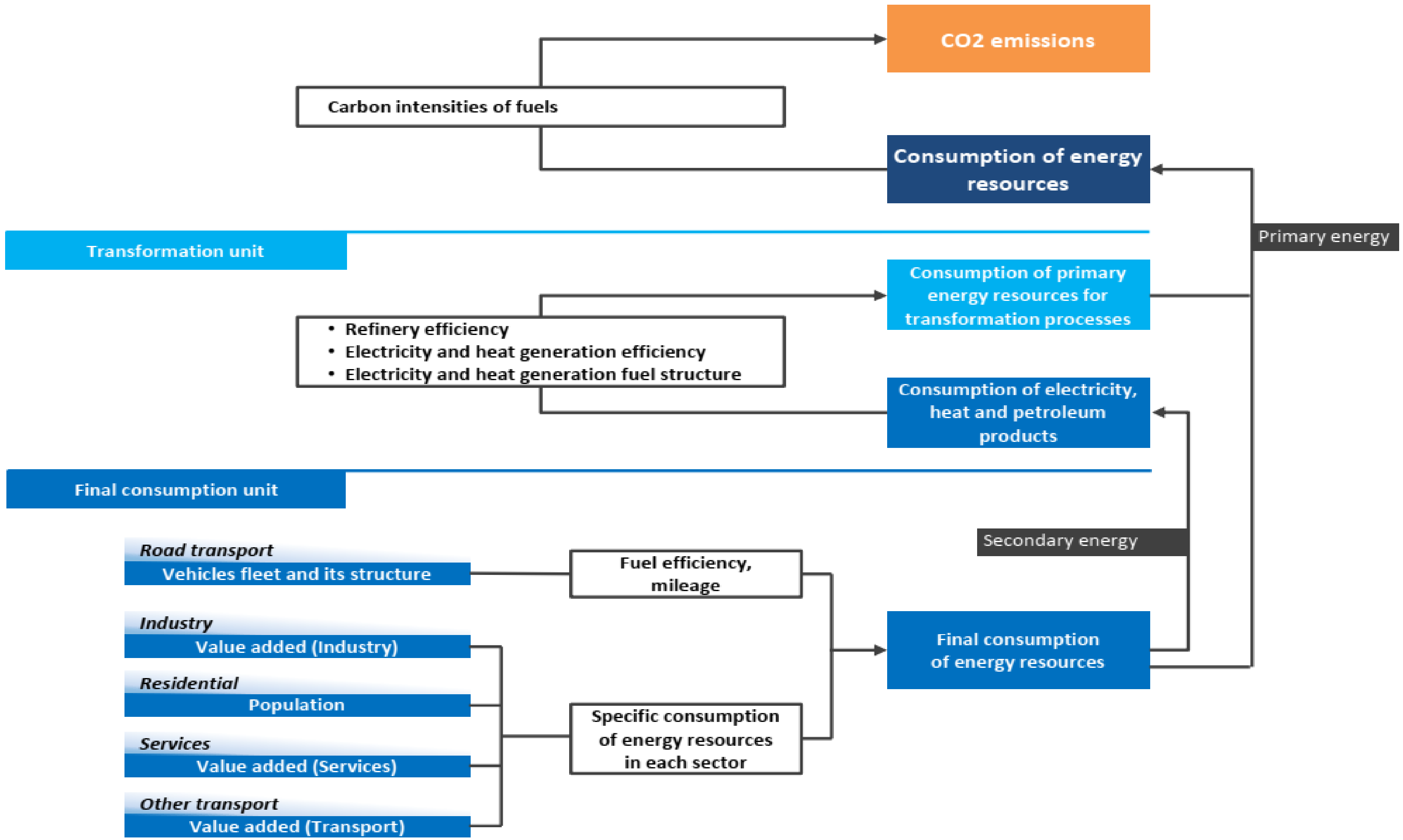

Figure 17: Solution algorithm for the 42 model

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4.4.8 Key parameters

Model 42 offers a simulation-based description of energy consumption processes. Therefore, in addition to socioeconomic and demographic characteristics, it requires parameters of CO_2 mitigation measures in terms of structural and technological features of the energy sector. A list of key parameters for all countries under consideration is given below:

- vehicle fleet and its structure (depending on the people's mobility hypothesis);
- structure of electricity and heat production (may be based on the countries' goals within the framework of the Paris Agreement or more ambitious targets);
- energy intensities of different sectors;
- fuel efficiency for cars and trucks (may be based on countries technical regulation of automotive industry and markets); and
- fuel efficiency for electricity and heat plants.

These parameters should be set to take into account existing goals of the national climate policy implemented by the countries under consideration, as well as to define the most efficient structure of the energy sector that is in line with the goals of the selected level of climate change mitigation (be that the Paris Agreement goals or scenarios of increased ambition).

4.4.9 Policy questions and SDGs

4.4.9.1 Key policies that can be addressed

As a simulation model, 42 predominantly works by adjusting the structural characteristic and efficiency parameters of energy-consuming sectors. In addition, the emission limits being adopted by countries may be used as a simulation target. The following policies can be implemented during the calculations:

- goals for renewable energy-based electricity generation in benchmark years;
- restrictions of the capacities/production for the power plants based on the fossil fuels;
- restriction or complete ban on sale and use of conventional (internal combustion engine) cars;
- stimulation of energy efficiency in terms of decreasing energy intensities of value added and energy consumption per capita; and
- restriction of CO_2 emissions associated with energy consumption.

42 may help to implement policy-relevant investigations, focused on searching the objective parameters, which are consistent with a low-carbon future, of national energy sectors of a wide list of countries. The overarching question the model aims to address is: *what is the structure of the energy balance, in consistency with the Paris Agreement?*

4.4.9.2 Implications for other SDGs

As an energy model, 42 is able track the goals for SDG §7 (affordable and clean energy), by exploring for example the share of low-carbon energy in the power sector and fuels in transportation.

4.4.10 Recent use cases

Table 25: Recent publications using the 42 model

Paper	Topic	Key findings
Ivanter et al.	Boosting the development of the Russian economy: priority actions (suggestions for the	The report highlights priority directions of the economic policy, primarily in investment activity, development of

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(2018)	main activities of the State until 2024)	the domestic market, as well as financial and organisational support for the suggested actions. 42 was used to determine the potential scenarios of future demand for Russian energy resources in the world
Semikashev et al. (2016)	Analysis and forecast of prospects for renewable energy development in the world until 2030	The goals of the countries under the Paris Agreement are studied. The structure of global energy consumption while achieving all stated goals is shown. The role of renewable energy in the global energy sector is assessed.
Uzyakov et al. (2016)	Integrated approach to the construction of agreed scenarios of world oil production, consumption and price	The article describes the evolution of the pricing mechanisms in the world oil market. We demonstrate the practical use of a modelling ensemble (which includes the 42 model) on the example of construction of agreed world oil production, consumption and price scenarios, interrelated with perspective parameters of the world economy and energy sector. The conditions and parameters of relatively high and low world oil prices scenarios are described.
Shirov et al. (2016)	Russia and Europe: Energy union of energy conflict? (Eight years after)	The article discusses current issues of interaction between Russia and the EU in the energy sector at the present stage. It is stated that the formation of an energy union has more advantages for each of the parties in comparison with the conflict scenario. Alternatives to Russia's energy policy in case of deterioration of trade and economic relations with the EU are given.

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4.5 The General Equilibrium Model of International-National Interactions between Economy, Energy and the Environment (GEMINI-E3)

4.5.1 Short overview

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium (CGE) model. It simulates all relevant markets, domestic and international, considered as perfectly competitive, which implies that the corresponding prices are flexible in markets for commodities (through relative prices), for labour (through wages), and for domestic and international savings (through rates of interest and exchange rates). Time periods are linked in the model through endogenous real rates of interest determined through the balancing of savings and investment. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses. There is one notable—and usual—exception to this general assumption of perfect competition, which concerns foreign trade. Goods of the same sector produced by the different countries are not supposed to be perfectly competitive; they are considered as economically different goods, more or less substitute according to an elasticity of substitution known as the Armington assumption. The main outputs of the GEMINI-E3 model are on a country and annual basis: carbon taxes, marginal abatement costs and prices of tradable permits (when relevant), effective abatement of CO_2 emissions, net sales of tradable permits (when relevant), total net welfare loss and components (net loss from terms of trade, pure deadweight loss of taxation, and net purchases of tradable permits when relevant), macro-economic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and data at the industrial level (e.g. change in production and in factors of production, and prices of goods).

4.5.2 Key features of the GEMINI-E3 model

4.5.2.1 Geographic coverage

In the version of GEMINI-E3 to be used in the PARIS REINFORCE project, the model divides the world into five countries (USA, China, India, Brazil and Russia) and six aggregated regions, with EU-28 being one. Table 26 gives the regional coverage of the model.

Table 26: Regional representation and countries included in each region in GEMINI-E3

Region ID	Geographic region	Countries
USA	United States of America	United States of America
EUR	European Union (28)	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
CHI	China	China, Hong Kong
IND	India	India
BRA	Brazil	Brazil
RUS	Russia	Russia
CSA	Central and South America countries	Mexico, Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean, Rest of North America, Rest of South America, Rest of Central America
ASI	Other Asian countries	Japan, South Korea, Mongolia, Taiwan, Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of East Asia, Rest of South Asia
MID	Middle East	Bahrain, Iran, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of Western Asia

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AFR	Africa	Egypt, Morocco, Tunisia, Benin, Burkina Faso, Cameroon, Cote d'Ivoire, Central Africa, South Central Africa, Ghana, Guinea, Nigeria, Senegal, Togo, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Botswana, Namibia, South Africa, Rest of Western Africa, Rest of South African Customs
ROW	Rest of the World	Australia, New Zealand, Canada, Switzerland, Norway, Albania, Belarus, Ukraine, Kazakhstan, Kyrgyzstan, Tajikistan, Armenia, Azerbaijan, Georgia, Israel, Rest of Oceania, Rest of Former Soviet Union, Rest of the World

4.5.2.2 Economic activities coverage

Like other CGE models, GEMINI-E3 covers all economic activities. In this version, the model divides the economy into eleven sectors, each one of which produces a good. Five of the sectors are related to the energy sector, three represent the transport sector, one covers the energy-intensive industries, and the remaining two sectors are agriculture and other goods and services. Table 27 provides the detailed industrial classification of GEMINI-E3.

Table 27: List of economic activities covered by GEMINI-E3

Sector ID	Sector
01	Coal
02	Crude oil
03	Natural gas
04	Refined petroleum products
05	Electricity
06	Agriculture
07	Energy intensive industries
08	Other goods and services
09	Land sector
10	Sea transport
11	Air transport

4.5.2.3 Energy system coverage

The energy sectors are represented similarly to other economic sectors by using nested Constant Elasticity of Substitution (CES) functions.

For electricity production, GEMINI-E3 distinguishes fossil fuel (i.e. coal, natural gas and oil power plants), nuclear, hydro, solar and wind power plants. Power generation is separated from the other activities (transmission and distribution) that appear through their factors of production at the top of the nesting structure. Power generation involves only two factors of production: capital and fuel for fossil fuel power plants and capital and a resource for renewables. With this nesting structure it is possible to better take into account the power generation portfolio and to represent inter-fuel substitutability as well as substitutability between fossil and renewable power generation. The model allows the use of carbon capture and storage (CCS) technology for coal and gas power plants when the carbon price is above the full cost of CCS.

Coal, crude oil and natural gas sectors include a fixed factor that represents the non-renewable resource associated with each fossil fuel energy. For these sectors we suppose that the domestic production is realised with this fixed factor and the other standard inputs (i.e. capital, labour, material and energy) through, again, a nested CES function.

Finally, refined petroleum products are produced from the basic input, i.e. crude oil. The model considers this specificity with a CES function between crude oil and other standards inputs at the top level of the nested CES structure.

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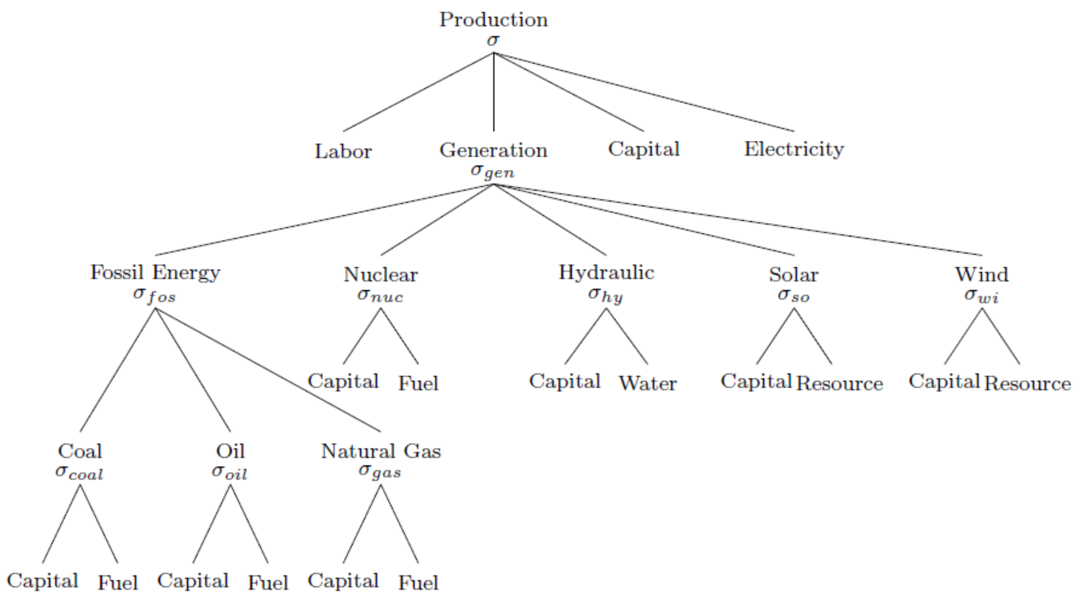

Figure 18: Nested CES production structure – Electricity in GEMINI-E3

4.5.2.4 Time periods

GEMINI-E3 is a recursive-dynamic, yearly model, with backward-looking (adaptive) expectations. The model simulates the global economy up to 2050. The base year of the model is 2014.

4.5.2.5 Database

The building and calibration of the CGE model rest on economic and energy data that are usually contained in comprehensive databases, specially established for this purpose. In particular, this version of GEMINI-E3 is built on GTAP-10 (Aguiar et al. 2019), a database that accommodates a consistent representation of energy markets in physical units (tons of oil equivalent) as well as detailed socio-accounting matrices in USD for a large set of countries or regions and bilateral trade flows. The GTAP database is completed by other information especially on indirect taxation and government expenditures, mainly coming from IEA, OECD and the International Monetary Fund (IMF). Important efforts have been put into harmonising all these sources of information. The result is a consistent social accounting matrix for each country/region.

4.5.3 Emissions granularity

Carbon emissions are directly computed from fossil energy consumption in physical quantities using coefficient factors that differ among firms (i.e. sectors), households and regions.

The representation of non-CO_2 emissions is based on the GTAP Non-CO_2 GHG emissions (NCGG) dataset (Rose and Lee, 2008). The database distinguishes several emissions of methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. The emissions of each source are linked to an activity level (or an economic driver). Abatements by gases are computed from the EPA abatement curves (EPA 2013).

Forests can mitigate GHGs by storing carbon, therefore GEMINI-E3 computes carbon sequestered by forest. We use forest mitigation supply functions computed by Favero et al. (2018), which use the Global Timber Model (GTM) to simulate the optimal management of forest land for climate change mitigation under several carbon price paths. These supply curves allow to compute the carbon sequestered by forest in each region.

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4.5.4 Socioeconomic dimensions

As other global macroeconomic models, GEMINI-E3 determines endogenously all economic variables by sectors, regions and years. The model computes the level of production (and the inputs associated: labour, capital, energy, and materials) but also demand (household demand, investment and export) by sectors/goods and regions. The prices associated to each good are determined endogenously. However, the dynamic of the model in the baseline scenario is mainly driven by exogenous variables that are listed hereafter.

4.5.4.1 Demographic assumptions

Population growth is exogenous and based on a forecast by the United Nations (United Nations 2019). The medium variant projection is usually retained. These projections allow to determine the growth of the labour supply using assumptions on participation rates by sex and age.

4.5.4.2 Technical progress and energy resources

Economic growth (i.e. GDP growth) and international energy prices (i.e. crude oil price, natural gas and coal prices) are usually based on IEA's forecasts in its World Energy Outlook (IEA, 2018). Technical progresses on labour as well as the dynamic of the energy resources are calibrated in order to reproduces the figures given by the World Energy Outlook.

4.5.4.3 Autonomous energy efficiency improvement

Finally, assumptions on technical progresses associated with energy consumption (i.e. autonomous energy improvement) are determined exogenously and usually calibrated on past data.

4.5.4.4 Economic indicators

GEMINI-E3 provides in a consistent way numerous economic variables at global and national/regional levels. The first set of variables is related to macroeconomic indicators such as:

- GDP
- Households and government consumptions
- Investment
- Exports and imports
- Government saving

These variables are expressed in volume (i.e. at the base year prices), but the prices associated to each of these macroeconomic aggregates are also computed (prices of GDP, of household consumption, etc.).

The second set refers to sectoral data:

- Production by sector
- Demand by sector and by usage (final demand, intermediate use)
- Production factors by sector (labour demand, energy consumption, capital, etc.

Again, for these sectoral data, changes in price and in volume are computed.

Finally, the model gives the international flows of goods and services (i.e. imports and exports) between the regions/countries described by the model.

4.5.5 Calibration of the model

The elasticities of substitution used in the supply and demand functions (i.e. in the nested CES functions) are based

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on a literature review. The other coefficients of the model are calibrated in order to reproduce exactly the reference year, i.e. 2014.

4.5.6 Economic rationale and model solution

For each sector and region, the model computes total demand as the sum of final demand (investment, consumption and exports) and intermediate consumptions by all sectors. Then, demand is split between imports and domestic production according to the Armington assumption. Domestic production technologies are described through nested CES functions, which differ according to the sector. For example, Figure 19 shows the nested CES production structure of the sector producing "other goods and services". Production is done with four aggregates: capital, labour, material and energy. In a second step (nest), material and energy are decomposed in individual goods using again CES functions.

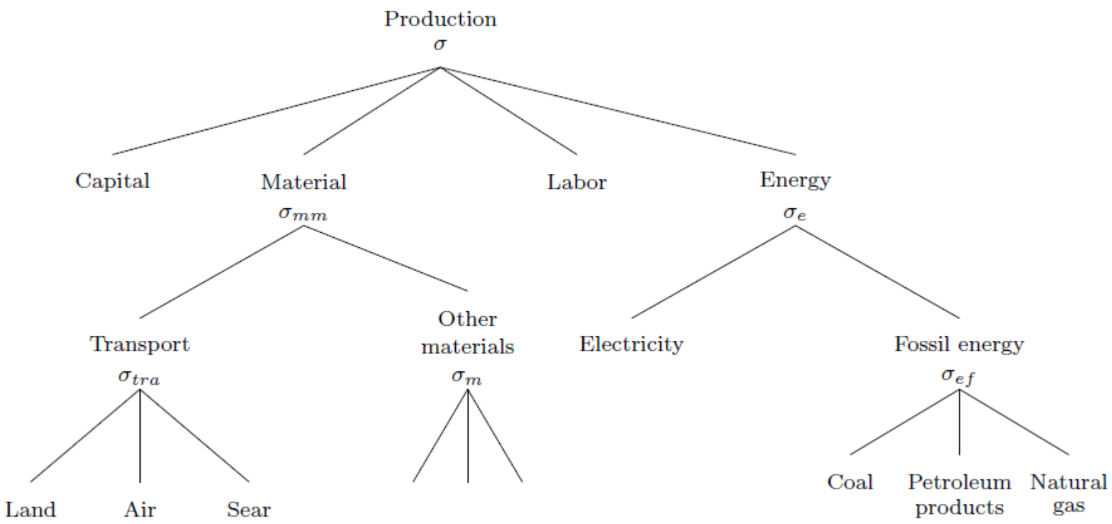

Figure 19: Nested CES production structure - Other goods and services in GEMINI-E3

Household behaviour consists of three interdependent decisions: 1) labour supply; 2) savings; and 3) consumption of the various goods and services. In GEMINI-E3, both labour supply and the rate of savings are assumed to be exogenous. Demand in the different commodities has prices of consumption and income (more precisely "spent" income, i.e. income after savings) as arguments and is derived from nested CES utility functions, described in Figure 19. At the first level of the consumption function, households choose between three aggregates: housing, transport and other consumptions. Energy consumption is split into two parts: for transportation and housing purposes. Transport demand is split into purchased and own transports. The model distinguishes three types of personal vehicles depending on the fuel used. Electric vehicles (EV), which are mainly dedicated to short or medium distance, and two other types using the same motorisation (i.e. internal combustion, or IC), one using petroleum products and the other biofuels. Each vehicle is characterised by a vehicle capital (called powertrain in Figure 20) and a type of fuel used (refined oil, biofuel or electricity).

Total government consumption is exogenous and its evolution over time, determined in the calibration of the model, is driven by the growth rates of the main aggregates of the economy. The model splits total consumption between goods based on fixed budget shares.

The exports are the sum of imports by all other countries/regions that are endogenously determined in the model.

Investment by products is derived from investment by sectors through a transfer matrix. Investment by sector is

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determined from an "anticipated" capital demand using the CES function of each sector. Anticipated production prices and demands are based on adaptive expectations.

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

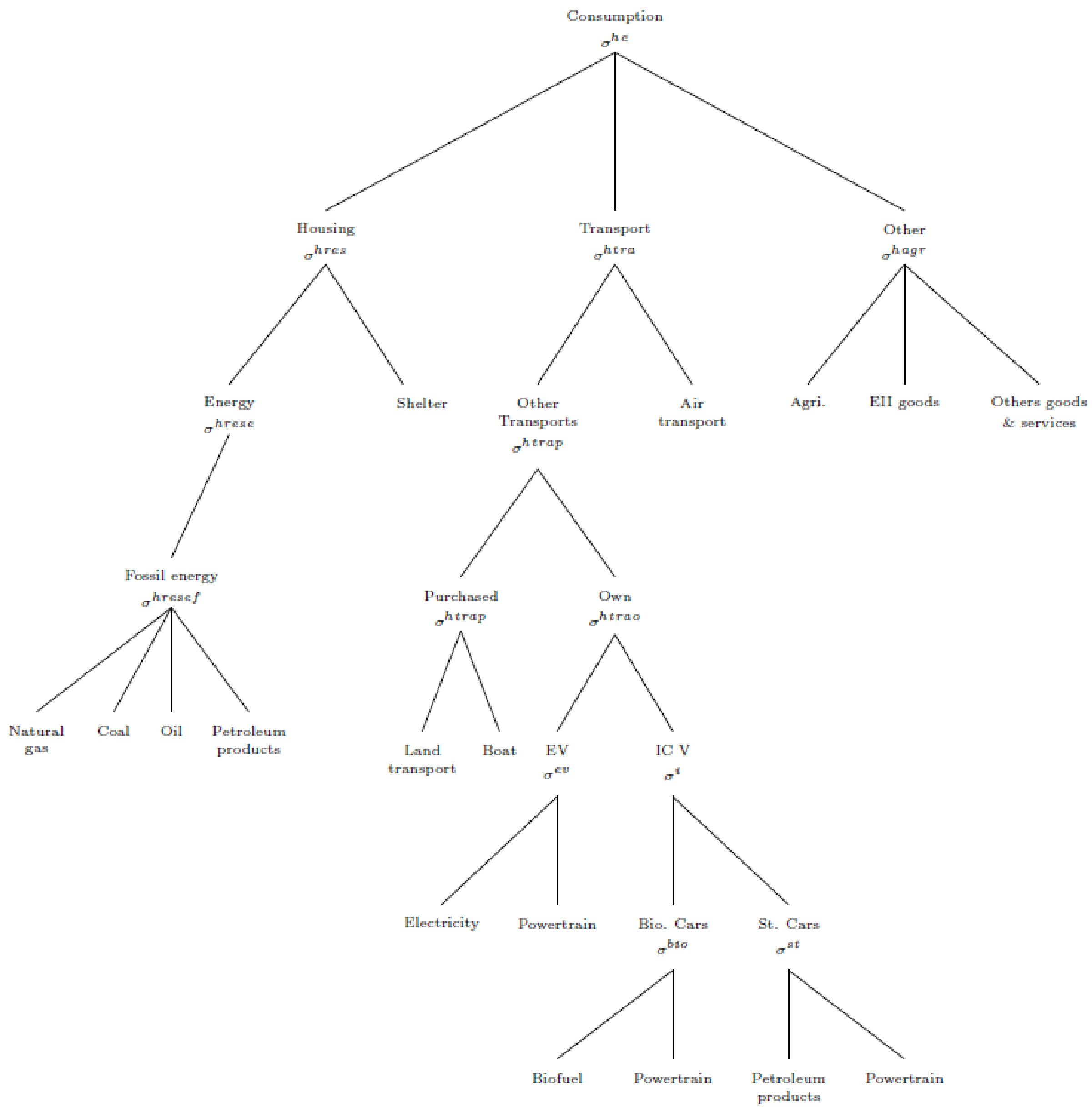

Figure 20: Nested CES Household consumption in GEMINI-E3

4.5.7 Policy questions and SDGs

4.5.7.1 Key policies that can be addressed

GEMINI-E3 was mainly designed to assess climate change and energy policies. The model can simulate climate change policies in two ways:

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1. First, based on climate targets (or pathways) as the ones defined by COP21 (Babonneau et al., 2018a), the model can evaluate the carbon prices that will be needed to reach these goals.
2. However, the model can also evaluate the impact on GHG emissions associated to a carbon tax defined by government (Babonneau et al., 2018c).

Climate change policies can be evaluated through the implementation of a carbon tax or an emissions trading system. The carbon tax can be uniform among countries/regions and sectors or be differentiated. The model can simulate a carbon tax framework coupled with an emissions trading system (Babonneau et al., 2018b). Within these climate policies, other constraints such as nuclear moratorium or non-price policies (such as emission standards) can also be analysed (Babonneau et al., 2018c).

Usually the carbon tax revenue is recycled by the government to households through a lump sum transfer in order to keep constant the surplus or deficit of the government. But other recycling rules can be implemented in the model.

GEMINI-E3 computes not only the carbon prices associated to climate change policies but also welfare changes. A consistent measure of welfare cost is the household's surplus. Deriving demand by households from a utility function then allows one to have a direct economic measure of the welfare cost of abatement policies. Households surplus may be directly reckoned from the numerical results of scenarios, for every year and every country/region, and they can be aggregated in various ways: either weighted by exchange rates and summed for a given year or period, or discounted through interest rates for a given country and then measuring the total discounted cost of the abatement policy. To eliminate the effects of changes in the relative prices of foreign trade, one must subtract the marginal gain (or loss) from changes in the terms of trade (GTT) to marginal welfare loss. This yields the so-called deadweight loss (DWL) of taxation. The GTTs represent spill-over effects due to changes in international prices. In a climate change policy, these GTTs come mainly from the drop in fossil energy prices that result from the decrease of world energy demand.

4.5.7.2 Implications for other SDGs

GEMINI-E3 was not originally designed to assess the sustainable development goals (SDGs). However, some indicators related to economic growth (SDG8), energy (SDG7) and climate (SDG13) can be evaluated directly from outputs of the model. Some other indicators may be analysed by performing some computations outside the model or by coupling GEMINI-E3 with other models.

4.5.8 Recent use cases

The model has been used by several national/international organisations like the Swiss Federal Office for the Environment (for example Babonneau et al., 2018c), the Centre d'Analyse Stratégique of the French Prime Minister, the United Nations Environment Programme (UNEP), the Energy Modeling Forum, etc. In the last twenty years, GEMINI-E3 has been extensively used to assess future climate and energy strategies at global and regional levels, including the research questions listed in Table 28.

Table 28: List of recent publications using the GEMINI-E3 model

Paper	Topic	Key findings
Vöhringer et al. (2019)	Analysis of economic consequences of climates in Switzerland, by covering health, buildings/infrastructure, energy,	For the considered impacts, welfare decreases by 0.37% to 1.37% in 2060 relative to a reference without climate change. Higher summer temperatures increase mortality and decrease

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	water, agriculture, and tourism, as well as the spill-overs to other sectors, and international effects	productivity. Contrariwise, tourism benefits from extended summer seasons. Regarding energy, increased demand for cooling is overcompensated by savings in heating.
Babonneau et al. (2018a)	Evaluation of the Paris Intended Nationally Determined Contributions (INDCs) and the design of fair agreements concerning additional abatements up to 2050	The analysis confirms the weakness of INDC pledges Nevertheless, we show that, with political determination, an equitable burden-sharing agreement can be achieved with very reasonable costs for all nations of approximately 0.8% of total discounted household consumption. With a more ambitious 1.5°C target, global cost is multiplied by a factor of four revealing the stringency of such an objective.
Babonneau et al. (2018b)	Evaluation of the recent developments of European climate policy from the perspective of the 2030 and 2050 European commitments; analysis of the European Effort Sharing Decision (ESD) proposed in July 2016 and of its cost per member state by 2030; considering the Brexit referendum that took place in June 23, 2016 in the United Kingdom	Results show that the EU burden-sharing based on GDP per capita implies very large discrepancies between Member States. If United Kingdom (UK) implements a Brexit, the 27 European countries could experience some welfare costs as additional abatements are required by the non-participation of UK to the ESD rules. In 2030, this additional cost is estimated at 8 billion € within a full Brexit. However, this cost is less significant than the one supported by UK which is approximately equal to 15 billion € in 2030.
Labriet et al. (2015)	Analysis of the impacts of changes in future temperatures on the heating and cooling services of buildings and the resulting energy and macro-economic effects at global and regional levels	At the global level, the climate feedback induced by adaptation of the energy system to heating and cooling is found to be insignificant, partly because heating and cooling-induced changes compensate and partly because they represent a limited share of total final energy consumption. However, significant changes are observed at regional levels, more particularly in terms of additional power capacity required to satisfy additional cooling services, resulting in increases in electricity prices.
Babonneau et al. (2018c)	Analysis of deep decarbonisation pathways for a small open economy (Switzerland) that lacks the usual avenues for large CO_2 reductions—heavy industry and power generation	Results show that the ambitious target is attainable at moderate welfare costs, even if it needs very high carbon prices, and that these costs are lower when either CO_2 can be captured and sequestered, or electricity consumption can be taxed sufficiently to stabilise it.
Joshi et al., (2016)	Assessment of the physical and economic consequences of sea-level rise (SLR) in the twenty first century	The simulation results suggest that the potential development of future coastal areas is a greater source of uncertainty than the parameters of SLR itself in terms of the economic consequences of SLR. At global level, the economic impact of SLR could be significant when loss of productive land along with loss of capital and forced displacement of populations are considered. Furthermore, highly urbanised and densely populated coastal areas of South East Asia, Australia and New Zealand are likely to suffer significantly if no protective measures are taken.

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4.6 The Intertemporal Computable Equilibrium System (ICES) model

4.6.1 Short overview

ICES is a recursive-dynamic multi-regional Computable General Equilibrium (CGE) model developed to assess impacts of climate change on the economic system and to study mitigation and adaptation policies. The model's general equilibrium structure allows for the analysis of market flows within a single economy and international flows with the rest of the world. This implies going beyond the "simple" quantification of direct costs, to offer an economic evaluation of second and higher-order effects within specific scenarios of climate change, climate policies and/or different trade and public-policy reforms in the vein of conventional CGE theory. The model is linked to the Aggregated Sustainable Development goal Index (ASDI) module that generates scenario and policy specific projections up to 2030 (2050) of selected SDG indicators allowing to assess the systemic implication of implementing a policy on countries' sustainability.

4.6.2 Key features of the ICES model

4.6.2.1 Geographic coverage

The ICES model has worldwide coverage. In PARIS REINFORCE, the globe will be broken down into 45 countries or regions (Table 29).

Table 29: Geographic coverage of ICES

No.	Countries/regions	Detail		No.	Countries/regions	Detail
1	Australia	Australia, Christmas Island, Cocos (Keeling) Islands, Heard Island and McDonald Islands, Norfolk Island		24	Germany	Germany
2	NewZealand	New Zealand		25	Greece	Greece
3	Japan	Japan		26	Italy	Italy
4	SouthKorea	South Korea		27	Poland	Poland
5	Bangladesh	Bangladesh		28	Spain	Spain
6	China	China, Hong Kong, Taiwan		29	Sweden	Sweden
7	India	India		30	UK	UK
8	Indonesia	Indonesia		31	RoEU	Austria, Cyprus, Denmark, Estonia, Hungary, Ireland, Latvia, Lithuania, Malta, Portugal, Slovakia, Slovenia, Bulgaria, Croatia, Romania
9	RoAsia	Mongolia, Democratic People's Republic of Korea, Macao, Cambodia, Lao PDR, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Brunei Darussalam, Myanmar, Timor-Leste, Nepal, Pakistan, Sri Lanka, Afghanistan, Bhutan, Maldives		32	RoEurope	Switzerland, Norway, Svalbard and Jan Mayen Islands, Iceland, Liechtenstein, Albania, Belarus, Ukraine, Moldova, Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Guernsey, Holy See (Vatican City State), Isle of Man, Jersey, Republic of Macedonia, Monaco, Montenegro, San Marino, Serbia
10	Canada	Canada		33	Russia	Russia
11	USA	USA		34	Turkey	Turkey
12	Mexico	Mexico		35	Egypt	Egypt
13	Argentina	Argentina		36	RoMENA	
14	Bolivia	Bolivia		37	Ethiopia	Ethiopia
15	Brazil	Brazil		38	Ghana	Ghana
16	Chile	Chile		39	Kenya	Kenya
17	Peru	Peru		40	Mozambique	Mozambique

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18	Venezuela	Venezuela		41	Nigeria	Nigeria
19	RoLACA	Colombia, Ecuador, Paraguay, Uruguay, Falkland Islands (Malvinas), French Guiana, Guyana, South Georgia and the South Sandwich Islands, Suriname, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Belize, Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Cuba, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, Trinidad and Tobago, Turks and Caicos Islands, Virgin Islands (US)		42	Uganda	Uganda
20	Benelux	Belgium, Luxembourg, Netherlands		43	SouthAfrica	South Africa
21	Czech Republic	Czech Republic		44	RoAfrica	Cameroon, Côte d'Ivoire, Senegal, Benin, Burkina Faso, Cape Verde, Gambia, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Sierra Leone, Togo, Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, Angola, Democratic Republic of the Congo
22	Finland	Finland		45	RoW	American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, United States Minor Outlying Islands, Vanuatu, Wallis and Futuna Islands, Bermuda, Greenland, Saint Pierre and Miquelon, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia, Antarctica, Bouvet Island, British Indian Ocean Territory, French Southern Territories
23	France	France				

4.6.2.2 Sectoral coverage

In each country, firms are grouped in 26 macro sectors that essentially comprise the economy (Table 30).

Table 30: ICES sectors

Sectors			
1	Agriculture	14	Hydro Electricity
2	Livestock	15	Nuclear Electricity
3	Processed Food	16	Other non-fossil Electricity
4	Forestry	17	Heavy Industries
5	Fishing	18	Light Industries

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6	Other Mining	19	Transport
7	Coal	20	Water
8	Oil	21	R&D
9	Gas	22	Market Services
10	Oil Products	24	Health
11	Fossil Electricity	25	Education
12	Solar Electricity	26	Public Services
13	Wind Electricity		

4.6.2.3 Database

ICES is a computable model: all the model behavioural equations are connected to the GTAP 8 database (Narayanan, Badri, & McDougall, 2012), which collects national social accounting matrices from all over the world and provides a snapshot of all economic flows in the benchmark year (2007). All economic flows related to fuel-specific energy production and consumption derive from GTAP-Power database (Peters, 2016) and are merged to GTAP 8 database.

In order to perform a sustainability analysis, the GTAP database has been integrated with international statistics in order to single out the following sectors: Research and Development (R&D), Education, and Health. For the R&D sector, the indicator "R&D expenditure as percentage of GDP" from the World Development Indicators - WDI (World Bank 2016) and the "share of R&D financed by Government, Firms, Foreign Investment and Other National" from the OECD Main Science and Technology Indicators (OECD 2016) are used for attributing R&D to the different economic agents. A similar approach has been used for Education and Health sectors. Data on overall expenditure on health and education have been obtained from the WDI database (World Bank 2016).

The ICES database has been further extended following the model developments regarding the public actor (Delpiazzo, Parrado, & Standardi, 2017). In addition to government revenues and expenditures already included in GTAP 8 database, other monetary flows have been made explicit: international transactions among governments (foreign aid and grants) and transactions between the government and the private households (net social transfers, interest payment on public debt to residents), flows among governments and foreign private households (interest payment on public debt to non-residents), and public debt.

4.6.3 Emissions granularity

The model's economic database is complemented with satellite databases on energy volumes (McDougall & Aguiar, 2008), CO_2 and non-CO_2 emissions (Rose & Lee, 2008; Lee, 2008), which include nitrous oxide (N_2O), methane (CH_4), and three fluorinated gases (F-gases). Both energy volumes and emissions have an endogenous dynamic in the models and evolve the former, according to energy sector production, and the latter, proportionally to energy combustion processes (CO_2 emissions) and sectoral and household use of agricultural and energy commodities. GHG emissions do not include emissions from LULUCF (Land Use, Land Use Change and Forestry). The median trend of GHG emissions across IAM scenarios (IIASA database) is targeted given the pattern of energy prices and adjusting sector-specific efficiency in energy use.

4.6.4 Socioeconomic dimensions

The model is largely driven by the set of possible futures envisioned by the climate change community and known as Shared Socioeconomic Pathways (SSPs) (O'Neill, et al., 2017). These are five possible futures with different mitigation/adaptation challenges and are characterised by different evolutions of main socioeconomic variables.

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SSPs can be linked to Representative Concentration Pathways (RCPs) that envision the GHG emission evolution and forcing and temperature rise due to specific patterns of socioeconomic growth (Riahi, et al., 2017).

SSPs provide future patterns for population, working age population and GDP at country level; the trend of the first two variables is completely exogenous in our simulation. The GDP trend is instead a target to be met through a mix of country and sector-specific productivities that are exogenously set (primary factor and total factor productivity).

4.6.5 Calibration of the model

In our reference scenarios, the growth of GDP, population and employment reproduces historical trends up to 2014 (WDI 2016) and then mimics SSP growth rates (OECD projections). Population trend relies on the WDI database (World Bank 2018) up to 2014 and then follows SSP growth rates (IIASA-WiC projections). Employment trends rely on the WDI database (World Bank 2018) up to 2010, then consider IIASA-WiC projections of working age population and other specific assumption of SSP storylines: converging participation and unemployment rates in the long run to a structural level.

4.6.6 Mitigation/adaptation measures

The ICES model includes a climate policy module that allows designing mitigation policies through explicit or implicit carbon taxes internalising or correcting the external costs of polluting activities.

In the former case, carbon taxes are introduced into the model through specific ad valorem rates depending on the source of emissions. Carbon tax rates are calculated for each emitting source as the corresponding ratio between tax revenues and the total tax base. Then, this ad valorem tax is added to the supply price and determines the market price that households and firms finally face.

In the case of implicit carbon tax, regional emission limits can be imposed (quotas). Countries/regions can exchange emission rights starting from an initial allocation of permits in order to comply with the quota. The emission trade generates the optimal allocation of abatement and the emission price. In the ICES policy module, we can restrict emissions training to a set of countries, as in the case of EU-ETS, and combine it with direct carbon taxation in other countries, or allow for a global emissions trading system.

In the module, it is also possible to design mitigation scenarios curbing the carbon leakage effect (Border Tax Adjustments - BTA).

In each country/region revenues are collected by government that can use them to reduce public debt or increase government expenditure or rebate them to support household income (transfer), to subsidise specific firms or production factors (endowments or intermediates), and to support other countries (international transfer to specific countries or to an international fund, e.g. Green Climate Fund).

In addition to carbon taxation, ICES can implement other mitigation options such as subsidising clean energy production and its use (with direct effect on government deficit), imposing behavioural shifts on household and firm energy demand (without direct effect on government deficit), improving efficiency in energy use (with/without direct effect on government deficit), and applying the above described instruments and constraints to the agriculture, livestock and forestry sectors.

4.6.7 Economic rationale and model solution

The core structure of ICES derives from the GTAP-E model (Burniaux & Truong, 2002), which in turn is an extension of the standard GTAP model (Hertel, 1997). The General Equilibrium framework makes it possible to account for

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economic interactions of agents and markets within each country (production and consumption) and across countries (international trade). Within each country the economy is characterised by n industries, a representative household and the government. Industries are modelled as representative cost-minimising firms, taking input prices as given. In turn, output prices are given by average production costs. The production functions (Figure 21) are specified via a series of nested CES functions. Primary factors—including natural resources, land, labour, and a capital-energy composite—constitute the Value Added Energy (QVAEN) nest, which is combined with intermediates (QF), in order to generate the output. Perfect complementarity is assumed between value added and intermediates. This implies the adoption of a Leontief production function. For sector i in region r, final supply (output), $Y_{i,r}$, results from the following constrained production cost minimisation problem for the producer:

$$\min PVAEN_{i,r}\ QVAEN_{i,r} + PF_{i,r}\ QF_{i,r}$$

$$s.t.\ \ Y_{i,r} = \min[QVAEN_{i,r}, QF_{i,r}\ ]$$

where PVAEN and PF are prices of the related production factors.

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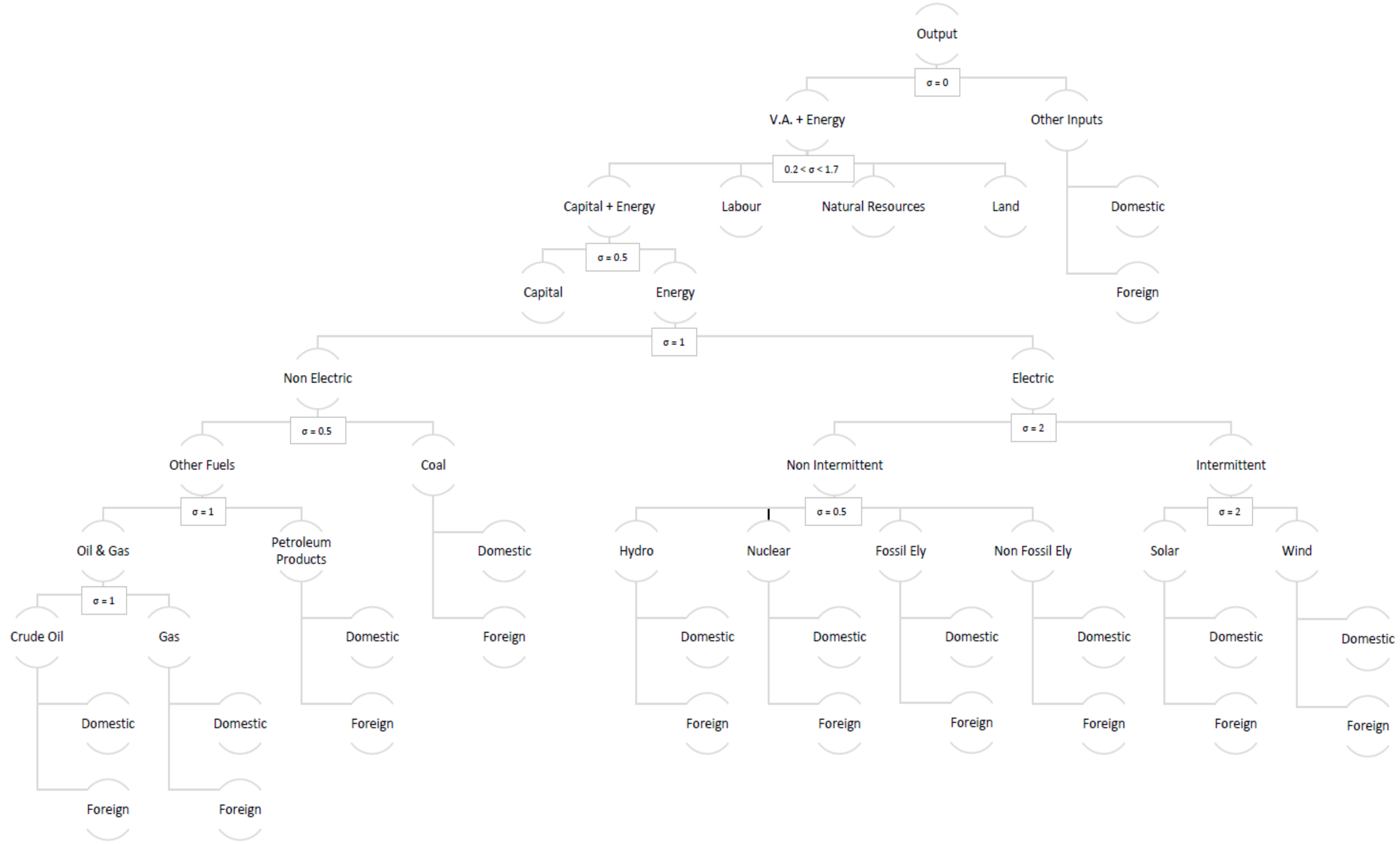

Figure 21: ICES production tree

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In the ICES production tree (Figure 21), the second nested level, on the left-hand side, represents the value added plus energy composite (QVAEN). This composite stems from a CES function that combines four primary factors: land (QLAND), natural resources (QNR), labour (QL) and the capital-energy bundle (QKE). Primary factor demand in turn derives from the first-order conditions of the following constrained cost minimisation problem for the representative firm:

$$\min\ P_{i,r}^{Land} LAND_{i,r} + P_{i,r}^{NR} NR_{i,r} + P_{i,r}^{L} L_{i,r} + P_{i,r}^{KE} KE_{i,r}$$

$$s.t.\ QVAEN_{i,r,t} = \left(LAND_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + NR_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + L_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + KE_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} \right)^{\frac{\sigma_{VAE}}{\sigma_{VAE}-1}}$$

In turn, the capital-energy bundle combines capital with a set of different energy inputs. In fact, energy inputs are not part of the intermediates, but are associated to capital in a specific composite. The energy bundle is modelled as an aggregate of electric and non-electric energy carriers. Electricity sector differentiates between intermittent and non-intermittent sources. Wind and solar, which are intermittent sources, are separated from non-intermittent sources: hydro, nuclear, fossil and other non-fossil electricity. Economic flows detailing production and consumption of energy relies on the GTAP-Power database (Peters, 2016).

The Non-Electric bundle is a composite of coal and energy from other fuels. The aggregate other fuels combine, in a series of subsequent nests, petroleum products with natural gas and crude oil. All elasticities regarding the inter-fuel substitution bundles are those from GTAP-E (Burniaux & Truong, 2002), while for the extended renewable electricity sectors we set those values considering different studies (Paltsev, et al., 2005; Bosetti, Carraro, Galeotti, Massetti, & Tavoni, 2006).

The demand of production factors (as well as that of consumption goods), can be met by either domestic or foreign commodities, which however are not perfectly substitutable according to the "Armington" assumption. In general, inputs grouped together are more easily substitutable among themselves than with other elements outside the nest. For example, the substitutability across imported goods is higher than that between imported and domestic goods. Analogously, composite energy inputs are more substitutable with capital than with other factors.

In the ICES model, as in GTAP, two industries are treated in a special way and are not related to any country, viz. international transport and international investment production. International transport is a world industry, which produces the transportation services associated with the movement of goods between origin and destination regions, thereby determining the cost margin between free-on-board (or f.o.b., before freight and insurance are added) and costs-insurance-freight (or c.i.f., inclusive of transportation margins) prices. Transport services are produced by means of factors submitted by all countries, in variable proportions. In a similar way, a hypothetical world bank collects savings from all regions and allocates investments in order to achieve equality in the absolute change of current rates of return.

Figure 22 describes the main sources and uses of regional income. In each region, a representative utility maximising household receives income, originated by the service value of national primary factors (natural resources, land, labour, and capital), that they own and sell to the firms. Capital and labour are perfectly mobile domestically but immobile internationally (investment is instead internationally mobile). Land and natural

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resources, on the other hand, are industry-specific and sluggish[1]. Land is used only by the agriculture and livestock sectors, and competition for land is only among these two sectors; natural resources are of three types: forestry and fishing, fossil (coal, oil and gas), and other mining. Whether a sluggish endowment is used by more than one sector, its optimal allocation responds to the revenue maximisation of a household subject to a transformation frontier (Constant Elasticity of Transformation, or CET, formulation). Both land and natural resources are monetary aggregate variables in the base year, but price and quantity changes are distinguishable in simulation years.

The regional income is used to finance aggregate household consumption and savings.

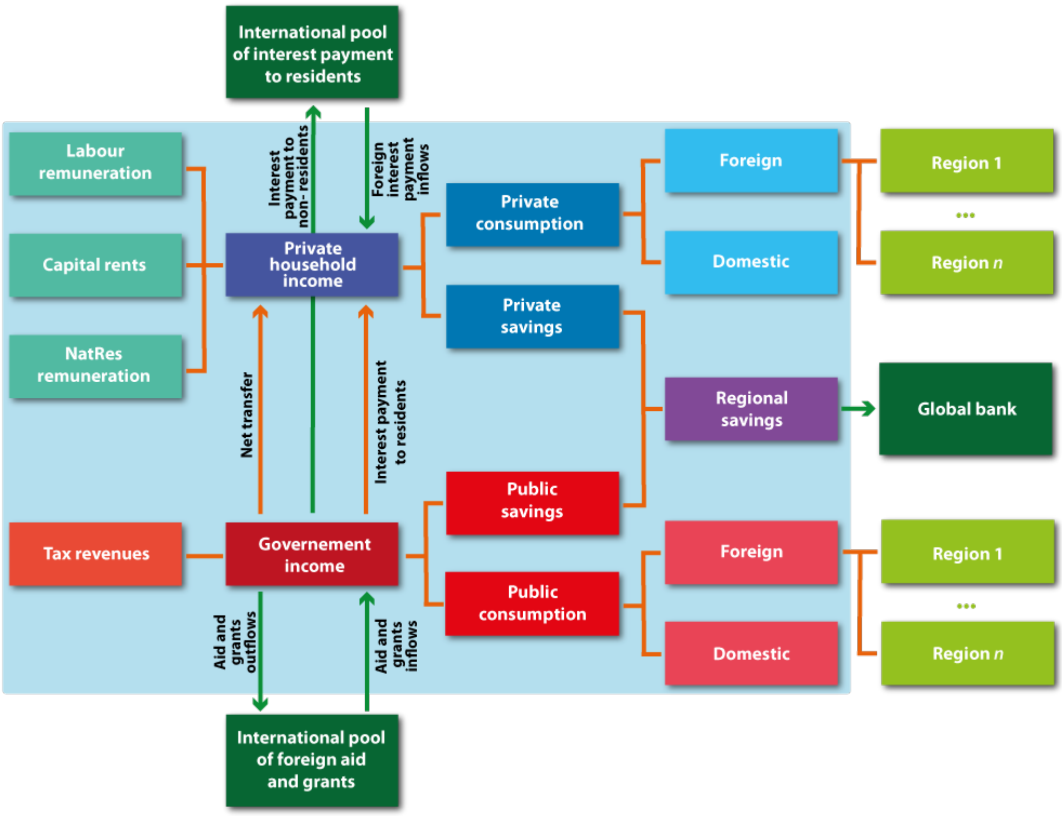

Figure 22: Sources and uses of regional household income in ICES

Government income equals to the total tax revenues from both private households and productive sectors, a series of international transactions among governments (foreign aid and grants), and national government-private transfers (Delpiazzo, Parrado, & Standardi, 2017). Both the government and the private household consume and save a fraction of their income according to a Cobb-Douglas function. The government income not spent is saved, and the sum of public and private savings determines the regional disposable saving, which enters the Global Bank as in the core ICES model.

Both private and public sector consumption are addressed to all commodities produced by each firm/sector. Public consumption is split into a series of alternative consumption commodities according to a Cobb-Douglas specification. However, almost all public expenditure is concentrated in the specific sector of non-market services, including education, defence and health. Private consumption is analogously addressed towards alternative goods and services, including energy commodities that can be produced domestically or imported. The functional

[1] Sluggish endowments are characterised by exogenous aggregate supply and frictions in the factor movement across sectors (no perfect elasticity), therefore, in equilibrium, returns of these endowments are not uniform across different uses.

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specification used at this level is the Constant Difference in Elasticities form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods[2].

The recursive-dynamic feature is described in Figure 23. Starting from the picture of the world economy in the benchmark year, by following socioeconomic (e.g. population, primary factors stocks and productivity) as well as policy-driven changes occurring in the economic system, agents adjust their decisions in terms of input mix (firms), consumption basket (households) and savings. The model finds a new general (worldwide and economy-wide) equilibrium in each period, while all periods are interconnected by the accumulation process of physical capital stock, net of its depreciation. Capital growth is standard along exogenous growth theory models and follows:

$$Ke_r = I_r + (1 - \delta)\, Kb_r$$

where Ke_r is the "end of period" capital stock, Kb_r is the "beginning of period" capital stock, δ is capital depreciation and I_r is endogenous investment. Once the model is solved at a given step t, the value of Ke_r is stored in an external file and used as the "beginning of period" capital stock of the subsequent step $t+1$.

The matching between savings and investments only holds at the world level; a fictitious world bank collects savings from all regions and allocates investments following the rule of highest capital returns.

As with capital, at each simulation step the government net deficit at the end of the period is stored in an external file and adds up to next year debt.

[2] Hanoch's constant difference elasticity demand system (Hanoch, 1975) has the following formulation: $1 = \sum_i B_i\, U^{Y_i R_i} \left(\frac{P_i}{X}\right)^{Y_i}$ where U denotes utility, P_i the price of commodity i, X the expenditure, B_i are distributional parameters, Y_i substitution parameters, and R_i expansion parameters. The constant difference elasticity in principle does not allow to define explicitly direct utility, expenditure or indirect utility functions. Accordingly, also explicit demand equations could not be defined. Fortunately, in a linearised equation system such as that used in GTAP, it is possible to obtain a demand function with price and expenditure elasticities.

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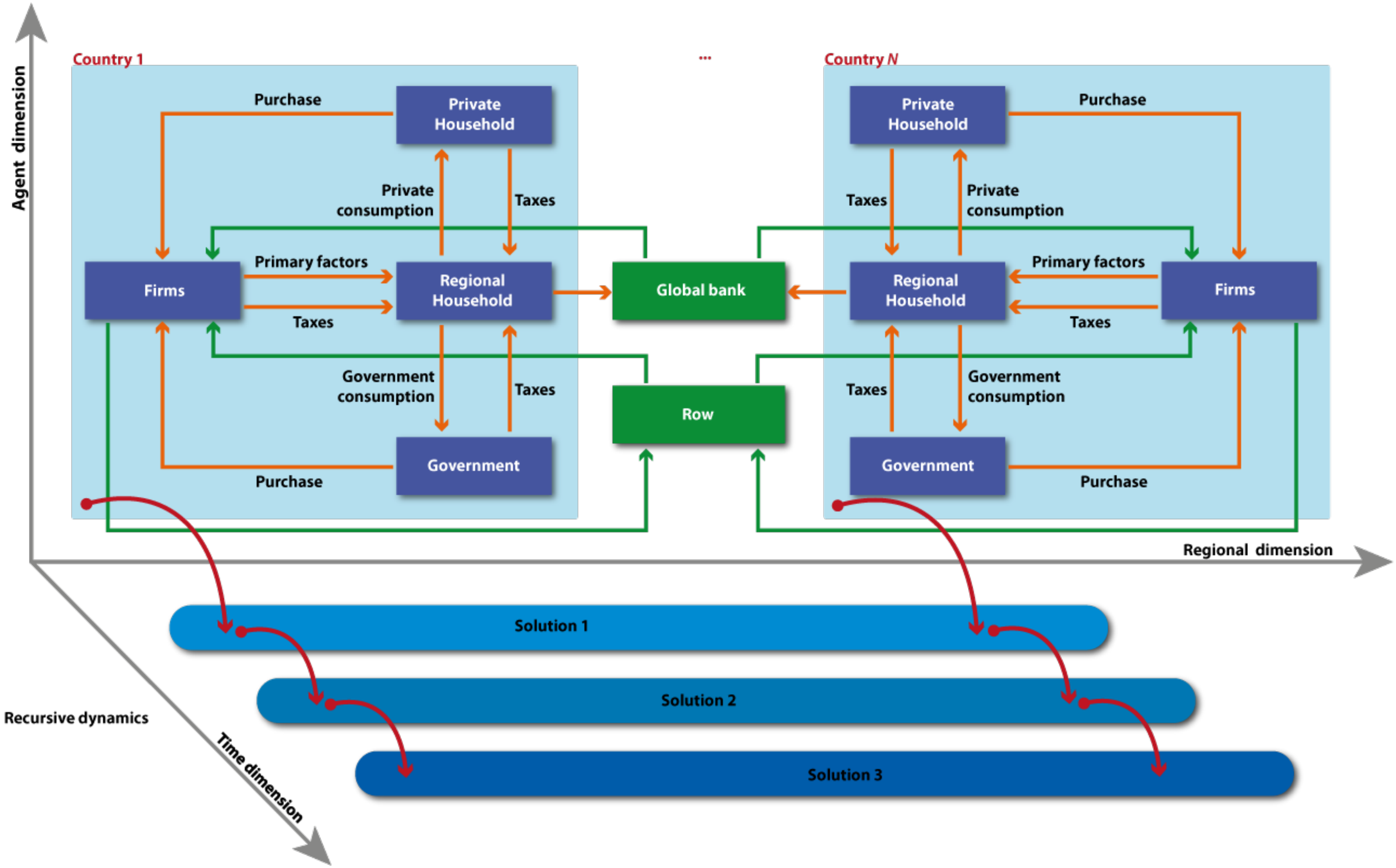

Figure 23: Recursive-dynamic feature of the ICES model

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4.6.8 Policy questions and SDGs

4.6.8.1 Key policies that can be addressed

The model can be used to address a series of climate policy questions, orienting on overall sustainability. These include a deeper understanding of the feasibility of deep decarbonisation targets and related costs; of trade-offs between climate action, economic development and other societal targets; of possible economic evolution trajectories according to different climate policy scenarios; as well as of socioeconomic synergies and trade-offs between mitigation policies and activities oriented on sustainable development.

By looking into GHG emissions, including non-energy and agriculture emissions, the model can inter alia be used to determine national/regional compliance with (intended) nationally determined contributions, and assess gaps from equitable and sustainable emissions.

The ICES model can also be used to assess economy-wide implications of adaptation strategies (the term of comparison in this case is generally a scenario with climate change impacts), e.g. understanding the benefits of changing the crop mix in the case of impacts in agriculture or of building preventive protections in the case of sea level rise causing land loss, or delving into behavioural shifts or efficiency changes associated to climate change (e.g. higher cooling demand), which are imposed exogenously before their economy-wide implications are assessed).

4.6.8.2 Implications for other SDGs

The ASDI (Aggregated Sustainable Development goal Index) module aims at offering a comprehensive assessment of future sustainability up to 2030 (with the capacity to extend the analysis to 2050) based upon 27 indicators related to the 17 Sustainable Development Goals, under different socioeconomic and policy scenarios. ASDI module combines a modelling framework (ICES model) with an empirical one (regression approach based on historical data) to offer an internally-consistent set-up for analysing future patterns of sustainability indicators and their inter-linkages (Figure 24).

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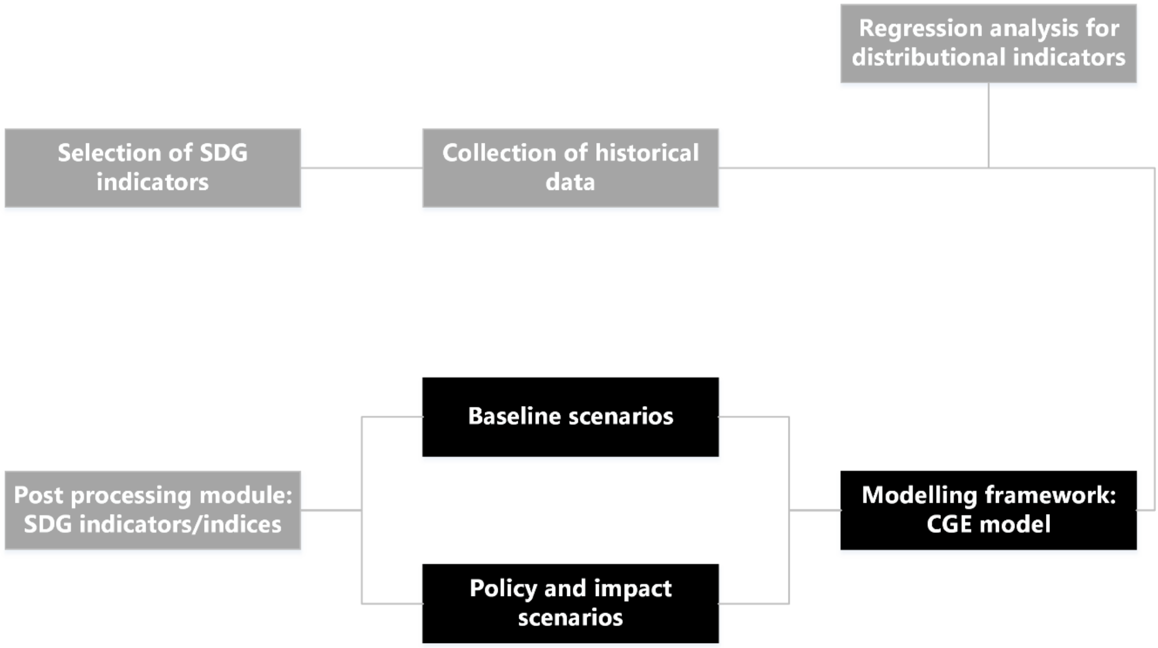

Figure 24: The ASDI module in ICES

Indicator selection is guided by the following requirements: relevance in measuring the SDG they refer to and connection with a specific quantitative SDG Target. Furthermore, ASDI indicators need to have good country coverage because the well-being assessment is worldwide and the comparability of the results of aggregation procedure requires excluding countries with missing values for at least one of ASDI indicators. ASDI indicators are at country level; the presence of a macro-economic model in our framework and the world coverage forces us to disregard more disaggregated indicators (gender, cohort, location-specific). Furthermore, the most stringent constraint in selecting ASDI indicators comes from the sustainability assessment: drawing the future path of SDG indicators depends on identifying their determinants (empirical analysis on the historical data and evidence from the literature), and, at the same time, depicting the future evolution of these determinants using the ICES model. The lack of any empirical evidence connecting an SDG indicator with one or more endogenous variable in our model determined its exclusion from ICES set of indicators. Table 31 lists all ASDI indicators, except for those referring to climate action (SDG 13).

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Table 31: ASDI indicators and main drivers for the ICES model

SDG	ASDI Indicator	Modelling Behaviour
SDG1	Poverty headcount ratio at \$1.90 a day (PPP2011) (% of population)	GDPPPP per capita and Palma ratio (regression)
SDG2	Prevalence of undernourishment (% of population)	GDPPPP per capita, squared GDPPPP per capita, Palma ratio, urban population share, agricultural production per capita (regression)
SDG3a	Physician density (per 1000 population)	Health expenditure per capita and private heath expenditure share (regression)
SDG3b	Healthy Life Expectancy (HALE) at birth (years)	Physician density, education expenditure per capita, electricity access, undernourishment prevalence, urban population share (regression)
SDG4	Youth literacy rate (% of population 15-24 years)	Public education expenditure per capita, urban population share (regression)
SDG6	Annual freshwater withdrawals, total (% of internal renewable water)	Domestic demand of water by agents: households, industry, agriculture (endogenous)
SDG7a	Access to electricity (% of total population)	GDPPPP per capita, GDPPPP per capita squared, electricity output per capita, urbanisation and Palma ratio (regression)
SDG7b	Renewable electricity (% in total electricity output)	Supply of Electricity from Renewables and Total Electricity (endogenous)
SDG7c	Primary energy intensity (MJ / \$PPP2011)	Total Primary Energy Supply and Real GDP (endogenous)
SDG8a	GDP per capita growth (%)	GDP (endogenous) and Population (exogenous)
SDG8b	GDP per person employed (\$PPP2011)	GDP (endogenous) and Employed Population (exogenous)
SDG8c	Employment-to-population ratio (%)	Exogenous
SDG9a	Manufacturing value added (% of GDP)	Value Added in Manufacturing and GDP (endogenous)
SDG9b	Total energy and industry-related GHG emissions over sectoral value added (t of CO_2e / \$PPP2011)	Industrial Emissions and Value Added in the Industrial sector (endogenous)
SDG9c	Research and development (R&D) expenditure (% of GDP)	R&D Value Added and GDP (endogenous)
SDG10	Palma ratio	Sectoral VA, public education expenditure per capita, unemployment and corruption control (regression)
SDG11	CO_2 intensity of residential and transport sectors (t of CO_2 / t of oil equivalent energy use)	Demand of Fossil Fuels and Emissions in Residential and Transport sectors (endogenous)
SDG12	Material productivity (\$PPP2011/ kg)	Material (mining) Use in Heavy Industry sector and GDP (endogenous)
SDG14	Marine protected areas (% of territorial waters)	Exogenous
SDG15a	Terrestrial protected areas (% of total land area)	Exogenous
SDG15b	Forest area (% of land area)	Land use in the Forestry sector (endogenous)
SDG15c	Endangered and vulnerable (animals and plants) species (% of total species)	Exogenous
SDG16	Corruption Perception Index	Exogenous
SDG17	General government gross debt (% of GDP)	GDP and government debt (endogenous)

Among ASDI indicators, sixteen are computed using model results, seven require regression analyses to be linked to them (SDG1, SDG2, SDG3a, SDG3b, SDG4, SDG7a, SDG10), and the remaining four are kept constant at historical levels (SDG14, SDG15a, SDG15c, SDG16). The collection of historical data of indicators relies on several international databases (World Development Indicators (World Bank, 2018), the UN database (United Nations, 2018), and World Income Inequality Database (WIID3.4) (United Nations, 2017b), and covers all available countries for the period 1990-2015.

Historical data are used for initialising indicators in the base year of the model (2007) and for estimating the basic

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relationships between the model's variables and indicators in the regression analysis phase. The ASDI module computes the values of the SDG indicators up to 2030 (2050) using the output of the ICES model. For the indicators not directly generated by the model, the estimated relationships from historical data with the regression analysis are used in an out-of-sample estimation procedure and combined with output variables of the model (main drivers are listed in Table 32). In order to derive SDG-specific indices (simple average of the underlying indicators) and the ASDI, ASDI indicator values are normalised, using a benchmarking procedure that identifies sustainable and unsustainable thresholds, and then aggregated.

4.6.9 Recent use cases

Table 32: List of recent publications using the ICES model

Paper	Topic	Key findings
(Campagnolo & Davide, 2019)	Potential synergies and trade-offs between emission reduction policies and sustainable development objectives (ex-ante assessment of the impacts of the NDCs on the SDGs of poverty eradication and reduced income inequality)	Our study finds that a full implementation of the emission reduction contributions, stated in the NDCs, is projected to slow down the effort to reduce poverty by 2030 (+4.2% of the population below the poverty line compared to the baseline scenario), especially in countries that have proposed relatively more stringent mitigation targets and suffer higher policy costs. Conversely, the impact of climate policy on inequality shows opposite sign but remains very limited. If financial support for mitigation action in developing countries is provided through an international climate fund, the prevalence of poverty will be slightly reduced at the aggregate level, but the country-specific effect depends on the relative size of funds flowing to beneficiary countries and on their economic structure.
(Campagnolo & Ciferri, 2018)	Investigation of the current well-being and the future sustainability of Italy	We provide evidence that in a scenario business-as-usual, Italy will not improve significantly its level of well-being. However, with a set of policies specifically targeted in 2030, the Italian sustainability would increase remarkably especially if all policies were implemented simultaneously.
(Campagnolo, et al., 2016)	Examination of recent developments in international climate policy, considering different levels of cooperation that may arise in light of the outcomes of the Conference of the Parties held in Doha	We find that the environmental component of sustainability improves at the regional and world level thanks to the implementation of climate policies. Overall sustainability increases in all scenarios since the economic and social components are affected negatively yet marginally. This analysis does not include explicitly climate change damages and this may lead to underestimating the benefits of policy actions. If the USA, Canada, Japan and Russia did not contribute to mitigating emissions, sustainability in these countries would decrease and the overall effectiveness of climate policy in enhancing global sustainability would be offset.

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(Virdis, Gaeta, De Cian, & Parrado, 2015)	Alternative pathways to achieve deep decarbonisation in Italy	The DDPs require considerable effort in terms of low-carbon resources and technologies. They also require considerable effort in economic terms. The cost changes, compared to a Reference Scenario, are significant: up to 30% higher cumulative net costs over the period 2010-2050. In particular, the emphasis switches from fossil fuel costs and operating costs towards investments in power generation capacity and more efficient technologies and processes
(Raitzer, et al., 2015)	Examination of potential regimes for regulating global GHG emissions through 2050 in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam.	The analysis affirms that a global climate arrangement that keeps mean warming below 2°C is in the economic interest of the region. Although the policy costs for such stabilisation during initial decades are not trivial, net benefits are found to far exceed net costs. The resource requirements are also not insurmountable, as costs are a smaller share of GDP than what the region has spent in recent years on fossil fuel subsidies. Moreover, the study finds that policy costs to achieve stabilisation sharply increase if actions to reduce emissions are delayed

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4.7 The Dynamic Integrated model of Climate and the Economy (DICE)

4.7.1 Short overview

DICE is a global integrated assessment model developed by Nordhaus (1992) that represents the economic, policy and scientific aspects of climate change. It integrates the climate system in the framework of economic growth theory. In this approach, society invests in capital goods, thereby reducing consumption today, in order to increase consumption in the future. Investing in emissions reduction reduces consumption today but also prevents damage from climate change and increases consumption possibilities in the future. The DICE model has been used and developed by researchers outside the consortium.

Figure 25 shows a schematic flow chart of the major modules and logical structure of the model. The economy module includes the factors that are driving the economic growth (labour, population, capital and technology) and also the emissions of GHGs. The DICE model includes also several geophysical relationships that link the economy with the different forces affecting climate change. These relationships include the carbon cycle, a radiative forcing equation, climate-change equations and a climate-damage relationship. A key feature of IAMs is that the modules operate in an integrated fashion rather than taking variables as exogenous inputs from other models or assumptions. Therefore, the damage of climate change affects the production/output via a damage function.

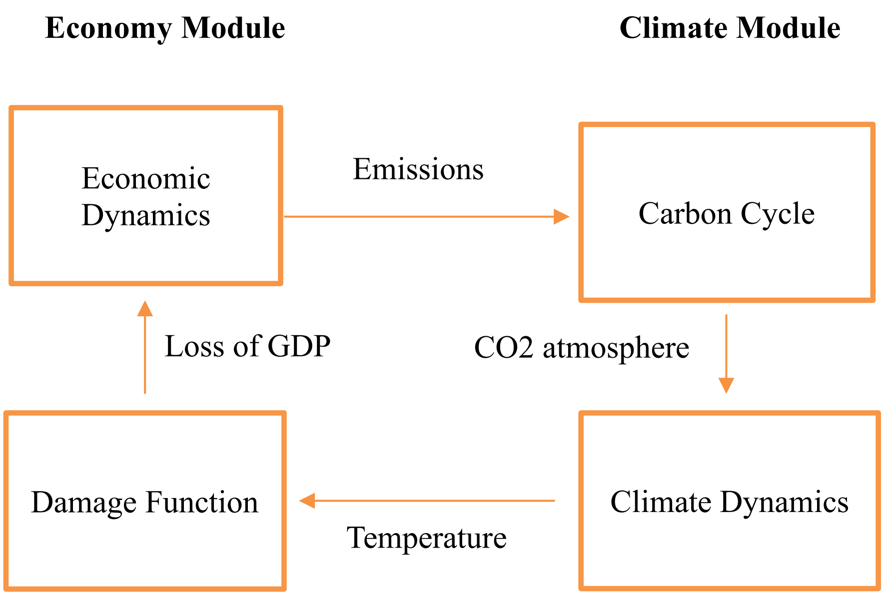

Figure 25: Structure of the DICE model

4.7.2 Technical specifications

In this section we include technical information on DICE extracted from Gonzalez-Eguino et al. (2016). More information can be found in Nordhaus and Sztorc (2013).

The model optimises a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption.

$$W = \sum_{t=1}^{T} U[c(t), L(t)]R(t).$$

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In this function, $c(t)$ is the per capita consumption, $L(t)$ is the population, and $R(t) = (1 + \rho)^{-t}$ is the discount factor of utility or welfare. ρ is the pure rate of social time preference or generational discount rate. The utility function is a constant elasticity function with respect to consumption of the form $U(c) = c^{1-\alpha}/(1 - \alpha)$. The parameter α is interpreted here as the generational inequality aversion.

Net output, $Q(t)$, is the gross output, $Y(t)$, reduced by damage, $\Omega(t)$, and mitigation costs, $\Lambda(t)$. This net output, a function of capital, labour and technology that explains economic growth, can be devoted to consumption, $C(t)$, and investment, $I(t)$. Labour is proportional to population, while capital accumulates according to an endogenous savings rate.

$$Q(t) = \Omega(t)[1 - \Lambda(t)]Y(t) = C(t) + I(t).$$

Damage from climate change, which is subject to large uncertainties, is represented in the DICE model by a quadratic function of globally averaged temperature change (T_{AT}). The damage function is defined as $\Omega(t) = D(t)/[1 + D(t)]$, where

$$D(t) = \psi_1 T_{AT}(t) + \psi_2[T_{AT}(t)]^2$$

The abatement cost is a function of the emissions reduction rate, $\mu(t)$, and is estimated to be highly convex, indicating that the marginal cost of reductions rises from zero more than linearly with the reduction rate:

$$\Lambda(t) = \theta_1[\mu(t)]^{\theta_2}.$$

Total emissions, $E(t)$, are fossil fuel and industrial emissions plus land-use change emissions, ELAND(t), and permafrost emissions, EPER(t). Fossil fuel and industrial CO_2 emissions are determined by the level of carbon intensity, $\sigma(t)$, times gross output, and reduced by the emissions reduction rate, $\mu(t)$. The only type of emissions subject to (endogenous) control in the DICE model is fossil fuel and industrial CO_2.

$$E(t) = \sigma(t)Y(t)[1 - \mu(t)] + E_{LAND}(t) + E_{PER}(t).$$

The geophysical equations link the GHG emissions to the carbon cycle, radiative forcing and temperature change. These equations are calibrated for the 21st century to large models or model experiments and have been updated (version 2013R) in line with AR5 of the IPCC (for example, in the current version, the equilibrium climate sensitivity has been reduced from 3 to 2.9). The following equation represents the equations of the carbon cycle for three reservoirs (j = AT, UP, and LO): atmosphere, upper oceans and biosphere, and lower oceans. All emissions flow into the atmosphere and the parameters φ_{ij} represent the flow of carbon between reservoirs per period.

$$M_j(t) = \varphi_{0j}E(t) + \sum_{j=1}^{3} \varphi_{i,j} M_i(t-1).$$

Finally, the relationship between CO_2 concentrations and increased radiative forcing is given by:

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t)$$

where F(t) is the change in total radiative forcing of greenhouse gases from anthropogenic sources and FEX(t) is an exogenous forcing (which includes non-CO_2 emissions and aerosols). For simplicity and transparency, we keep all aspects of the original DICE model unaltered. In this way, our results can easily be compared to previous findings obtained with the same model.

4.7.3 Regional, sectoral and GHG coverage

DICE is a global model. Therefore, it is not disaggregated between sectors, technologies or regions. The model

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includes CO_2 emissions from fossil fuel combustion endogenously and CO_2 from other sources exogenously. Non-CO_2 emissions are included aggregated as exogenous radiative forcing.

4.7.4 Recent use cases and limitations

DICE has been helpful in illustrating the economic cost and damage from climate action under different circumstances (Nordhaus, 2014; Moore and Diaz, 2015; Butler et al., 2014; or González-Eguino, 2016) However, different studies have shown that the results of the DICE model are very sensitive to the choice of the damage function (Pindyck, 2013), especially beyond 2°C. Therefore, some authors have used the DICE model using alternative damage functions (Ackerman et al., 2010 or Gonzalez-Eguino et al., 2017) and a sensitivity analysis of key parameters. Finally, the DICE model is an aggregated model that captures the economic cost of mitigation using only a cost function. Therefore, it cannot capture the complexity of the mitigation options of large-scale IAMs, such as, for example, the GCAM or TIAM models.

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4.8 The Energy-Environment-Economy Global Macro-Economic (E3ME) model

4.8.1 Short overview

The Energy-Environment-Economy Macro-Econometric model (E3ME – www.e3me.com) is a computer-based model of the world's economic and energy systems and the environment. It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessments, forecasting and research purposes.

E3ME assesses the interactions between the economy, energy and the environment. As a global model, based on the full structure of the economic national accounts, E3ME is capable of producing a broad range of economic indicators. In addition, there is range of energy and environment indicators.

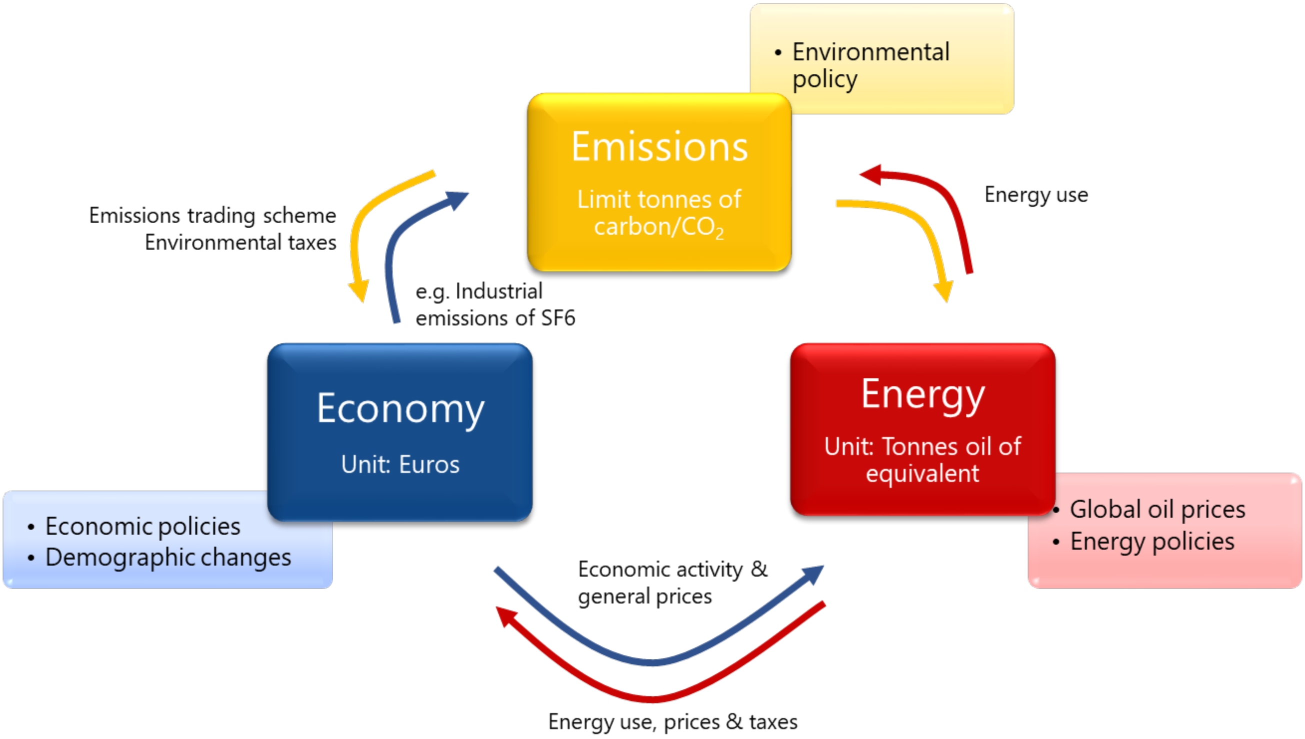

Figure 26: E3ME as an E3 Model

4.8.2 Key features of the E3ME model

4.8.2.1 Geographic coverage

The E3ME model covers the entire globe in 61 regions, which comprise most major economies (including China, India, Russia, Brazil, Japan, Canada, Mexico, Indonesia, and the United States of America), the EU, at the regional level as well as at the national level (Member States plus candidate countries), and other countries' economies separately or regionally grouped.

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Table 33: Countries and regions covered in E3ME

Geographic region	Countries
AOPEC	Africa OPEC
AR	Argentina
AT	Austria
AU	Australia
BE	Belgium
BR	Brazil
BU	Bulgaria
CA	Canada
CH	Switzerland
CN	China
CO	Colombia
CR	Croatia
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EL	Greece
EN	Estonia
ES	Spain
FI	Finland
FR	France
HU	Hungary
ID	Indonesia
IN	India
IR	Ireland
IS	Iceland
IT	Italy
JP	Japan
KA	Kazakhstan
KO	Korea
LT	Lithuania
LV	Latvia
LX	Luxembourg
MA	North Macedonia
MA	Malaysia
MT	Malta
MX	Mexico
NG	Nigeria
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RAI	Rest of Annex I
RASEAN	Rest of ASEAN
RLA	Rest of Latin America
RO	Romania
ROA	Rest of Africa
ROPEC	Rest of OPEC
RU	Russian Federation
SA	Saudi Arabia
SI	Slovenia

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SK	Slovenia
SW	Sweden
TK	Turkey
TW	Taiwan
UK	United Kingdom
UR	Ukraine
US	United States of America
ZA	South Africa
ROW	Rest of World

4.8.2.2 Sectoral coverage

The model covers the entire economy, into up to 69 sectors, with considerable detail of service sectors, as well as up to 43 categories of consumer expenditure.

4.8.2.3 Energy system coverage

Twenty-three different users of twelve different fuel types are included in the model.

4.8.3 Emissions granularity

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

4.8.4 Socioeconomic dimension

The E3ME model includes thirteen types of household, including income quintiles and socioeconomic groups, such as the unemployed, inactive and retired, plus an urban/rural split.

It is built to create annual projections up until 2050 over these main model dimensions (although, theoretically, it can be used up to 2100).

4.8.5 Policy questions

4.8.5.1 What kind of questions can the model address?

E3ME can be used for both forecasting and evaluating the impacts of an input shock through a scenario-based analysis. The shock could be, for example, a change in policy or a change in economic assumptions. The analysis can be either forward-looking (ex-ante) or evaluating previous developments in an ex-post manner.

As such, E3ME is well-suited to examine questions regarding changes in policies. The primary strength of E3ME lies in its use as a platform for the analysis of scenarios. As E3ME is a global Energy-Economy-Environment model, it is capable of addressing such questions as follows:

- Changes in the economy and labour market associated with changes in policy
- Impacts of changes in energy demand and changes in the composition of energy technologies
- The effect of policy on environmental indicators including emissions (consumption and production-based) and material use

4.8.5.2 What kind of answers can the model provide?

As noted, E3ME is designed to form annual projections up to 2050. Therefore, E3ME is commonly used to compare

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scenario projections. The following, non-exhaustive list shows the most common model outputs:

- GDP and the aggregate components of GDP (household expenditure, investment, government expenditure and international trade)
- Sectoral output and GVA, prices, trade and competitiveness effects
- International trade by sector, origin and destination
- Consumer prices and expenditures
- Sectoral employment, unemployment, sectoral wage rates and labour supply
- Energy demand, by sector and by fuel, energy prices
- Rebound and spill-over effects
- CO_2 emissions by sector and by fuel
- Other air-borne emissions
- Material demands

Given the wide range of both economic and environmental output indicators, and the high degree of disaggregation, E3ME is capable of providing detailed projections of the impacts of policies on both the regional level as well as the sectoral level.

4.8.6 Recent use cases

Table 34: List of recent publications using the E3ME model

Paper	Topic	Key findings
Wood et al. (2019)	Historical impacts of globalisation and future impacts of climate policies on international emission transfers	The results suggest that absolute embodied emissions will plateau at current levels or slowly return to pre-2008- crisis levels, and differences between the NDC and baseline scenarios imply that NDC policies will not result in significant carbon leakage. The share of national footprint embodied in imports, at least for countries with ambitious decarbonisation policies, will likely increase. This suggests that, despite the world-wide stabilisation of emissions transfers, addressing emissions embodied in imports will become increasingly important for reducing carbon footprints.
Gramkow and Anger-Kraavi (2019)	Exploring a transformation of Brazil's economy, with a focus on manufacturing sectors, while contributing to the Paris targets	Findings highlight that the correct mix of green stimulus can help modernise and decarbonise the Brazilian manufacturing sectors and the country's economy grow faster (by up to 0.42% compared to baseline) while its carbon dioxide (CO_2) emissions decline (by up to 14.5% in relation to baseline). Investment levels increase, thereby strengthening exports' competitiveness and alleviating external constraints to long-term economic growth in net terms. Scaling up green fiscal stimulus in manufacturing sectors globally needs to be considered as one of the main policy measures helping with transformation to a low-carbon economy, especially in the developing world.
Bachner et al., 2019	Uncertainties in the economy-wide assessment of decarbonisation pathways, in the European iron and steel sector	We show that the effects depend strongly on the technology choice, the prevailing macroeconomic states as well as regional characteristics. The underlying socioeconomic development and the climate policy trajectory, with a to date expected range of variation, seem to play a less important

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		role. Particularly, we find that the choice of model, with its underlying macroeconomic theory, influences the sign and magnitude of macroeconomic effects and thus should be well understood by both modellers and policymakers. We emphasise that model assumptions should be transparent, results sought to be derived across a range of possible contexts, and presented together with the conditions under which they are valid. To that end, co-design and co-production in research would support its relevance.
Spijker et al., 2019	Integrated impacts of low-emission transitions in the Dutch livestock sector	Findings suggest that each low-emission transition pathway has its own unique ‘footprint’ of positive and negative side-effects. This footprint is largely shaped by the combination of existing and new technologies, practices and behavioral patterns. We consider the findings relevant for climate policy and transition governance processes where there is a need to develop robust transition pathways that meet different development goals and to overcome implementation barriers for the selected low emission technologies and practices.
Silaen et al., 2018	Understanding the potential of bioenergy for an energy transition in Bali	Quantitative research using the E3ME model identified economic benefits of biogas deployment, but also that increased LPG use due technological constraints of biogas could cause a potential increase of national CO_2 emissions. Policy stakeholders agreed that LPG subsidies hindered the biogas development and biogas should be considered in Indonesia’s Medium-Term National Development Plan. These factors, in addition to co-benefits of biogas, should be considered while drafting the development plan.

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Bibliography

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R., & van der Mensbrugghe, D. (2019). The GTAP data base: version 10. Journal of Global Economic Analysis, 4(1), 1-27.

Babonneau, F., Haurie, A., & Vielle, M. (2018). From COP21 pledges to a fair 2 C pathway. Economics of Energy & Environmental Policy, 7(2).

Babonneau, F., Haurie, A., & Vielle, M. (2018). Welfare implications of EU effort sharing decision and possible impact of a hard Brexit. Energy Economics, 74, 470-489.

Babonneau, F., Thalmann, P., & Vielle, M. (2018). Defining deep decarbonization pathways for Switzerland: an economic evaluation. Climate Policy, 18(1), 1-13.

Bachner, G., Mayer, J., Steininger, K. W., Anger-Kraavi, A., & Smith, A. (2019). Uncertainties in the economy-wide assessment of decarbonization pathways - The case of the European iron and steel. Ecological Economics (submitted, under review)

Barker, T. (1998). The effects on competitiveness of coordinated versus unilateral fiscal policies reducing GHG emissions in the EU: an assessment of a 10% reduction by 2010 using the E3ME model. Energy Policy, 26(14), 1083-1098.

Bernard, A., & Vielle, M. (2008). GEMINI-E3, a general equilibrium model of international–national interactions between economy, energy and the environment. Computational Management Science, 5(3), 173-206.

Bosello, F., Parrado, R., Rosa, R., & Eboli, F. (2015). REDD in the carbon market: A general equilibrium analysis. Environmental Modeling & Assessment, 20(2), 103-115.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., & Tavoni, M. (2006). WITCH a world induced technical change hybrid model. The Energy Journal, 13-37.

Burniaux, J. M., & Truong, T. P. (2002). GTAP-E: an energy-environmental version of the GTAP model. GTAP Technical Papers, 18.

Butler, M. P., Reed, P. M., Fisher-Vanden, K., Keller, K., & Wagener, T. (2014). Inaction and climate stabilization uncertainties lead to severe economic risks. Climatic change, 127(3-4), 463-474.

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., ... & McJeon, H. (2017). The SSP4: A world of deepening inequality. Global Environmental Change, 42, 284-296.

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R. Y., ... & Hejazi, M. (2019). GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems. Geoscientific Model Development (Online), 12(PNNL-SA-137098).

Campagnolo, L., & Ciferri, D. (2018). Is Italy on the Pathway for Achieving Sustainable Development Goals?. In Getting Globalization Right (pp. 209-239). Springer, Cham.

Campagnolo, L., & Davide, M. (2019). Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. World Development, 122, 96-109.

Campagnolo, L., Carraro, C., Davide, M., Eboli, F., Lanzi, E., & Parrado, R. (2016). Can climate policy enhance sustainability?. Climatic change, 137(3-4), 639-653.

Chiodi, A., Gargiulo, M., Gracceva, F., De Miglio, R., Spisto, A., Costescu, A., & Giaccaria, S. (2016). Unconventional oil and gas resources in future energy markets - A modelling analysis of the economic impacts on global

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

energy markets and implication for Europe. Publications Office of the European Union, Luxembourg. doi: 10.2790/83538.

Crow, D. J., Giarola, S., & Hawkes, A. D. (2018). A dynamic model of global natural gas supply. Applied energy, 218, 452-469.

Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change, 42, 200-214.

Delpiazzo, E., Parrado, R., & Standardi, G. (2017). Extending the Public Sector in the ICES Model with an Explicit Government Institution.

Doukas, H., & Nikas, A. (2020). Decision support models in climate policy. European Journal of Operational Research, 280 (1), pp. 1-24.

Doukas, H., Nikas, A., González-Eguino, M., Arto, I., & Anger-Kraavi, A. (2018). From integrated to integrative: Delivering on the Paris Agreement. Sustainability, 10(7), 2299.

Eboli, F., Parrado, R., & Roson, R. (2010). Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. Environment and Development Economics, 15(5), 515–533.

Edmonds, J. A., Wise, M. A., & MacCracken, C. N. (1994). Advanced energy technologies and climate change: An analysis using the global change assessment model (GCAM) (No. PNL-9798). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Favero, A., Sohngen, B., Huang, Y., & Jin, Y. (2018). Global cost estimates of forest climate mitigation with albedo: a new integrative policy approach. Environmental Research Letters, 13(12), 125002.

Fawcett, A. A., Iyer, G. C., Clarke, L. E., Edmonds, J. A., Hultman, N. E., McJeon, H. C., ... & Creason, J. (2015). Can Paris pledges avert severe climate change?. Science, 350(6265), 1168-1169.

Few, S., Gambhir, A., Napp, T., Hawkes, A., Mangeon, S., Bernie, D., & Lowe, J. (2017). The impact of shale gas on the cost and feasibility of meeting climate targets—a global energy system model analysis and an exploration of uncertainties. Energies, 10(2), 158.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., ... & Ermolieva, T. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change, 42, 251-267.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., ... & Ermolieva, T. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change, 42, 251-267.

Gambhir, A., Drouet, L., McCollum, D., Napp, T., Bernie, D., Hawkes, A., ... & Lowe, J. (2017). Assessing the feasibility of global long-term mitigation scenarios. Energies, 10(1), 89.

Gambhir, A., Napp, T. A., Emmott, C. J., & Anandarajah, G. (2014). India's CO2 emissions pathways to 2050: Energy system, economic and fossil fuel impacts with and without carbon permit trading. Energy, 77, 791-801.

Giarola, S., Mittal. S, Vielle, M., Perdana, S., Campagnolo, L., Delpiazzo, E., Bui, H., Anger-Kraavi, A., Kolpakov, A., Sognnaes, I., Peters, Hawkes, A., Koberle, A., Grant, N., Gambhir, A., Nikas, A., Doukas, H., Moreno, J, van de Ven, D-J. (Reviewed and revised). Challenges in the harmonisation of global integrated assessment models: a comprehensive methodology to reduce model response heterogeneity, Science of the Total Environment.

González-Eguino, M., & Neumann, M. B. (2016). Significant implications of permafrost thawing for climate change

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

control. Climatic Change, 136(2), 381-388.

González-Eguino, M., Neumann, M. B., Arto, I., Capellán-Perez, I., & Faria, S. H. (2017). Mitigation implications of an ice-free summer in the Arctic Ocean. Earth's Future, 5(1), 59-66.

Gramkow, C., & Anger-Kraavi, A. (2019). Developing Green: A case for the Brazilian manufacturing industry. Sustainability (submitted, under review)

Hanoch, G. (1975). Production and demand models with direct or indirect implicit additivity. Econometrica (pre-1986), 43(3), 395.

Hertel, T. W. (1998). Global trade analysis: modeling and applications. Cambridge university press.

Huang, Z., Hejazi, M., Tang, Q., Vernon, C. R., Liu, Y., Chen, M., & Calvin, K. (2019). Global agricultural green and blue water consumption under future climate and land use changes. Journal of Hydrology, 574, 242-256.

IEA (2018). World Energy Outlook, International Energy Agency, Paris

Ivanter V.V., Porfiryev B.N., Sorokin D.E., Eskindarov M.A., Maslennikov V.V., Shirov A. A., Abdikeev N.M., Abramova M. A., Bogachev Yu.S., Goncharenko L.I., Govtvan' O. Dzh., Gusev M.S., Dubova S.E., Ershov M.V., Zubets A.N., Kolpakov A. Yu., Ksenofontov M.N., Kuvalin D. B., Mikheeva N.N., Moiseev A.K., Potapenko V.V., Solyannikova S.P., Stroev P.V., Tolkachev S. A., Uzyakov M.N., & Fedotova M. A. (2018). How to Boost the Development of the Russian Economy: Priority Actions (Suggestions for the Main Activities of the State until 2024). Finance: Theory and practice, 22 (1), pp. 4-15. (In Russian).

Joshi, S. R., Vielle, M., Babonneau, F., Edwards, N. R., & Holden, P. B. (2016). Physical and economic consequences of sea-level rise: A coupled GIS and CGE analysis under uncertainties. Environmental and Resource Economics, 65(4), 813-839.

Kelly, D. L., & Kolstad, C. D. (1999). Integrated assessment models for climate change control. International yearbook of environmental and resource economics, 2000, 171-197.

Kerdan, I. G., Giarola, S., & Hawkes, A. (2019). A novel energy systems model to explore the role of land use and reforestation in achieving carbon mitigation targets: A Brazil case study. Journal of Cleaner Production.

Kerdan, I. G., Giarola, S., Jalil-Vega, F., & Hawkes, A. (2019). Carbon Sequestration Potential from Large-Scale Reforestation and Sugarcane Expansion on Abandoned Agricultural Lands in Brazil. Polytechnica, 1-17.

Kerdan, I. G., Jalil-Vega, F., Toole, J., Gulati, S., Giarola, S., & Hawkes, A. (2019). Modelling cost-effective pathways for natural gas infrastructure: A southern Brazil case study. Applied Energy, 255, 113799.

Kerdan, I.G., Giarola, S., & Hawkes, A. (2019). Implications of Future Natural Gas Demand on Sugarcane Production, Land Use Change and Related Emissions in Brazil, J. sustain. dev. energy water environ. syst.

Labriet, M., Joshi, S. R., Vielle, M., Holden, P. B., Edwards, N. R., Kanudia, A., ... & Babonneau, F. (2015). Worldwide impacts of climate change on energy for heating and cooling. Mitigation and Adaptation Strategies for Global Change, 20(7), 1111-1136.

Lee, H. L. (2008). The combustion-based CO2 emissions data for GTAP Version 7 Data Base. Center for Global for Global Trade Analysis, Purdue Universty: West Lafayette.

Loulou, R., & Labriet, M. (2008). ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Computational Management Science, 5(1-2), 7-40.

Markandya, A., Sampedro, J., Smith, S. J., Van Dingenen, R., Pizarro-Irizar, C., Arto, I., & González-Eguino, M. (2018). Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. The

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Lancet Planetary Health, 2(3), e126-e133.

McDougall, R. A., & Aguiar, A. H. (2008). GTAP 7 Data Base: Chapter 11: Energy Data. In B. Narayanan, & L. Terrie (Eds.), Global Trade, Assistance, and Production: The GTAP 7 Data Base. Center for Global Trade Analysis, Purdue University: Walmsley.

Moore, F. C., & Diaz, D. B. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. Nature Climate Change, 5(2), 127.

Napp, T. A., Few, S., Sood, A., Bernie, D., Hawkes, A., & Gambhir, A. (2019). The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. Applied energy, 238, 351-367.

Napp, T., Bernie, D., Thomas, R., Lowe, J., Hawkes, A., & Gambhir, A. (2017). Exploring the feasibility of low-carbon scenarios using historical energy transitions analysis. Energies, 10(1), 116.

Narayanan, G., & Badri, A. A., and R. McDougall (2012):"Global Trade, Assistance, and Production: The GTAP 8 Data Base". Center for Global Trade Analysis, Purdue University.

Nikas A., Doukas H., Papandreou A. (2019) A Detailed Overview and Consistent Classification of Climate-Economy Models. In: Doukas H., Flamos A., Lieu J. (eds) Understanding Risks and Uncertainties in Energy and Climate Policy. Springer, Cham

Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches. Journal of the Association of Environmental and Resource Economists, 1(1/2), 273-312.

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. Science, 258(5086), 1315-1319.

Nordhaus, W.D., & Sztorc., P. (2013). DICE 2013R: Introduction and User's Manual. Available at: http://www.econ.yale.edu/~nordhaus/homepage/documents/ DICE_Manual_103113r2.pdf.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., ... & Levy, M. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, 42, 169-180.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J. R., Sarofim, M. C., ... & Babiker, M. H. (2005). The MIT emissions prediction and policy analysis (EPPA) model: version 4. MIT Joint Program on the Science and Policy of Global Change.

Peters, J. C. (2016). The GTAP-power data base: disaggregating the electricity sector in the GTAP data base. Journal of Global Economic Analysis, 1(1), 209-250.

Pindyck, R. S. (2013). Climate change policy: what do the models tell us?. Journal of Economic Literature, 51(3), 860-72.

Raitzer, D. A., Bosello, F., Tavoni, M., Orecchia, C., Marangoni, G., & Samson, J. N. G. (2015). SouthEast Asia and the economics of global climate stabilization. Asian Development Bank.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature communications, 10(1), 3277.

Reilly, J. M., Edmonds, J. A., Gardner, R. H., & Brenkert, A. L. (1987). Uncertainty analysis of the IEA/ORAU CO_2

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

emissions model. The Energy Journal, 8(3), 1-29.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... & Lutz, W. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environmental Change, 42, 153-168.

Rose, S., & Lee, H. L. (2009). Non-CO2 greenhouse gas emissions data for climate change economic analysis. In Economic analysis of land use in global climate change policy (pp. 109-140). Routledge.

Sachs, J., Meng, Y., Giarola, S., & Hawkes, A. (2019a). An agent-based model for energy investment decisions in the residential sector. Energy, 172, 752-768.

Sachs, J., Moya, D., Giarola, S., & Hawkes, A. (2019b). Clustered spatially and temporally resolved global heat and cooling energy demand in the residential sector. Applied Energy, 250, 48-62.

Samir, K. C., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change, 42, 181-192.

Schwanitz, V. J. (2013). Evaluating integrated assessment models of global climate change. Environmental modelling & software, 50, 120-131.

Semikashev V.V., Kolpakov. A.Yu. Merkulov S.K., & Terentiev N.E. (2016). Analysis and forecast of prospects for renewable energy development in the world until 2030. Alternative energy as a factor of modernization of the Russian economy: trends and prospects. Collection of scientific papers. Publisher: Scientific consultant limited liability company, Moscow. (In Russian).

Shirov A.A., Semikashev V.V., Yantovskii A.A., & Kolpakov A.Y. (2016). Russia and Europe: Energy union of energy conflict? (Eight years after). Studies on Russian Economic Development, 27 (2), pp. 127-137.

Silaen, M., Taylor, R., Bößner, S., Anger-Kraavi, A., Chewpreecha, U., Badinotti, A., & Takama, T. (2019). Bioenergy in Bali: applying mixed-research methods to understand potential for an energy transition, Environmental Innovation and Societal Transitions (submitted, under review)

Sinus sociovision. (2017). Informationen zu den sinus-milieus. Available at: http://www.sinus-institut.de/sinus-loesungen/sinus-meta-milieus-weltweit/, accessed: 2017-01-15.

Sognnaes, I., Gambhir, A., van de Ven, D-J, Nikas, A., Anger-Kraavi, A., Bui, H., Campagnolo, L., Delpiazzo, E., Doukas, H., Giarola, S., Grant, N., Hawkes, A., Koberle, A., Kolpakov, A., Mittal, S., Moreno, J., Perdana, S., Rogelj, J., Vielle, M., Peters, G. (In review). A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. Nature Climate Change.

Spijker, E., Anger-Kraavi, A., Pollitt, H., & Van de Ven, D.-J. (2019). Evaluating integrated impacts of low-emission transitions in the livestock sector, Environmental Innovation and Societal Transitions (submitted, under review)

United Nations (2019). World population prospects 2019, online edition, Department of Economic and Social Affairs, Population Division.

US EPA. (2013). Global mitigation of non-CO2 greenhouse gases: 2010-2030.

Uzyakov M.N., Yantovskiy A.A., Ksenofontov M.Yu., Semikashev V.V., & Kolpakov A.Yu. (2016). Integrated approach to the construction of agreed scenarios of world oil production, consumption and price. Oil industry, 11, pp. 8-14. (In Russian).

Van de Ven, D. J., Sampedro, J., Johnson, F. X., Bailis, R., Forouli, A., Nikas, A., Yu, S., Pardo, G., de Jalón, S.G., Wise,

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

M., & Doukas, H. (2019). Integrated policy assessment and optimisation over multiple sustainable development goals in Eastern Africa. Environmental Research Letters, 14(9), 094001.

Virdis, M. R., Gaeta, M., De Cian, E., Parrado, R., Martini, C., Tommasino, M. C., & Antimiani, A. (2015). Pathways to deep decarbonization in Italy. SDSN-IDDRI: Paris, France.

Vöhringer, F., Vielle, M., Thalmann, P., Frehner, A., Knoke, W., Stocker, D., & Thurm, B. (2019). Costs And Benefits Of Climate Change In Switzerland. Climate Change Economics, 10(02), 1950005.

Wood, R., Grubb, M., Anger-Kraavi, A., Pollitt, H., Rizzo, B., Alexandri, E., ... & Tukker, A. (2019). Beyond peak emission transfers: historical impacts of globalization and future impacts of climate policies on international emission transfers. Climate Policy, 1-14.

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.