PARIS
REINFORCE

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D6.1 DOCUMENTATION OF NATIONAL/ REGIONAL MODELS FOR COUNTRIES OUTSIDE EUROPE

WP6 – Promoting sustainable transitions across the globe

Version: 1.10R

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Lead Beneficiary	Grantham Institute, Imperial College London			
Responsible Author	Ajay Gambhir	Email	a.gambhir@imperial.ac.uk	
		Phone	+44 20 7594 6363	
Contributors	Jorge Moreno, Dirk-Jan van de Ven (BC3); Kathleen Vaillancourt, Zsolt Lengyel (IEECP); Maurizio Gargiulo, Rocco de Miglio, Alessandro Chiodi (E4SMA); Andrey Kolpakov, Alexander Shirov (IEF-RAS); Xi Yang (CUP); Diego Silva Herran (IGES); Camila Gramkow (CDS/UnB); Swapnil Shekhar (TERI); Alexandros Nikas (NTUA)			
Reviewer(s):	Alexandros Nikas (NTUA); Francesco Bosello (CMCC); Jorge Moreno (BC3); Philippe Thalmann (EPFL)			
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EC Summary Requirements

1. Changes with respect to the DoA

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

2. Dissemination and uptake

This deliverable will 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 national/regional level in countries and regions outside Europe, 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 models for non-European countries, 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 describes in detail the key attributes of the models to be used in PARIS REINFORCE to develop and examine sustainable development and decarbonisation pathways for major and less emitting countries and regions outside of Europe (e.g. USA, Canada, Mexico, China, India, Japan, Brazil, and the Central Asian Caspian region); global IAMs (documented in D7.1) will also be used in WP6 analyses.

The nine documented models are predominantly energy system models: they provide a detailed representation of the extraction of primary fuels, conversion of those fuels into energy sources that can be utilised in each major sector of the economy that requires energy (the building, transportation, industrial manufacturing and agricultural sectors). Many of these models also represent, albeit in a relatively simplified way, non-energy emissions from the agricultural and land use sectors.

Each model can simulate a broad range of policies, with most models able to accommodate emissions constraints, carbon taxation and subsidies, product or technology regulations or bans, and energy efficiency targets. However, the models can only represent behavioural changes in a limited manner.

Finally, the models have a varying degree of representation of factors relevant to the achievement of SDGs and consideration of adaptation measures: the models do not project the impacts of a changing climate, but some models can take exogenous climate change into account to some extent.

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	EPU N·T·U·A
BC3 - Basque Centre for Climate Change	ES	bc3
Bruegel - Bruegel AISBL	BE	bruegel
Cambridge - University of Cambridge	UK	UNIVERSITY OF CAMBRIDGE
CICERO - Cicero Senter Klimaforskning Stiftelse	NO	°CICERO
CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	IT	cmcc
E4SMA - Energy, Engineering, Economic and Environment Systems Modelling Analysis	IT	E4SMA
EPFL - École polytechnique fédérale de Lausanne	CH	EPFL
Fraunhofer ISI - Fraunhofer Institute for Systems and Innovation Research	DE	Fraunhofer ISI
Grantham - Imperial College of Science Technology and Medicine - Grantham Institute	UK	Grantham Institute Climate Change and the Environment
HOLISTIC - Holistic P.C.	GR	HOLISTIC
IEECP - Institute for European Energy and Climate Policy Stichting	NL	IEECP
SEURECO - Société Européenne d'Economie SARL	FR	SEURECO ERAΣME
CDS/UnB - Centre for Sustainable Development of the University of Brasilia	BR	Centro de Desenvolvimento Sustentável UnB
CUP - China University of Petroleum-Beijing	CN	
IEF-RAS - Institute of Economic Forecasting – Russian Academy of Sciences	RU	IEF RAS
IGES - Institute for Global Environmental Strategies	JP	IGES
TERI - The Energy and Resources Institute	IN	teri

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Executive Summary

This document describes in detail the key attributes of the models that will be used in PARIS REINFORCE to develop and examine sustainable development and decarbonisation pathways for major and less emitting countries and regions outside of Europe. These regions include the USA, Canada, Mexico, China, India, Japan, Brazil, and the Central Asian Caspian region. The models will complement those models that will be used to examine detailed sustainable development and decarbonisation pathways within the European Union (which are documented in D5.1), as well as at the global level (which are documented in D7.1). This does not exclude models documented in D7.1 from being used to undertake analyses at the national and/or regional level outside Europe, but rather focuses on the models that will only be used in this respect; other models documented in D7.1 will also be used in WP6 analyses, provided they have sufficient geographical granularity.

The document first compares (in Sections 1 and 2) key attributes of the different models used, setting out their geographical coverage, their approach to producing low-carbon pathways under different emissions targets and/or policies, the range of mitigation measures and policies that they can simulate, and the range of their outputs which are relevant to the assessment of broader sustainable development goals, as well as the consideration of adaptation measures. Finally, Section 3 includes detailed documentation for each individual model, in a consistent format and structure to aid detailed inter-model comparisons.

The models are predominantly energy system models, which means that they provide a detailed representation of the extraction of primary fuels, conversion of those fuels into energy sources that can be utilised in each major sector of the economy that requires energy (the building, transportation, industrial manufacturing and agricultural sectors). Many of these models also represent, albeit in a relatively simplified way, non-energy emissions from the agricultural and land use sectors.

Most of the energy models are designed with the objective of achieving a given emissions target, or simulating given climate policies (such as a carbon tax or regulation), whilst minimising energy system costs, or maximising economic welfare. One model, of Brazil, is not an optimisation model, but a simulation one, developed to embed an agent-based approach to energy systems modelling.

Within this optimisation paradigm, four different model types can be identified. First, the CONTO model represents the Russian economy as different business and domestic sectors, tracking the inputs into and outputs from each sector into other sectors, so as to simulate real economic activity. This includes tracking energy inputs and outputs, where the choice of fuels used depends on the energy technologies deployed in each sector, itself determined by different technology and fuel costs, so as to maximise profits in each sector over time, and determine the economic growth path with or without climate policies or constraints.

Next are a family of country-level models based on the "GCAM" global integrated assessment model, representing Canada, USA and Japan. These models, unlike CONTO, are not economy-representing models but rather detailed representations of the greenhouse gas emitting systems (energy, agricultural and land systems) in each of the countries represented. These systems' emissions constraints or policies are met in a cost-optimal way in each of a distinct set of time periods. Each time period is treated independently of the potential decisions that could be made in future periods, to represent a degree of myopia in policy decision-making.

One family of models, the MUSE-Brazil one, belongs to the agent-based simulation models. MUSE-Brazil is an energy-system model which explicitly characterises the decision-making of firms and consumers in the energy system, capturing a variety of features of market imperfections due to agents' choices and due to a limited foresight approach to the modelling of energy futures.

The final family of models are based on the "MARKAL-TIMES" framework developed and managed under the

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auspices of the International Energy Agency's Energy Technology Systems Analysis Programme (ETSAP). These models cover China, India, North America (including Canada, USA and Mexico) and the Central Asia Caspian region (including Kazakhstan, Uzbekistan, Turkmenistan and Azerbaijan). In contrast to the GCAM models, the MARKAL-TIMES models achieve a cost-optimisation by simultaneously considering all time periods in a given model simulation, as part of an assumption of "perfect foresight" of decision makers acting on emissions constraints or policies.

Each model can simulate a broad range of policies, with most models able to accommodate emissions constraints, carbon taxation and subsidies, product or technology regulations or bans, and energy efficiency targets. However, the models can only represent behavioural changes in a limited manner, principally through changing levels of demand for energy in response to economic development and energy price changes.

Finally, the models have a varying degree of representation of factors relevant to the achievement of sustainable development goals and consideration of adaptation measures. In the former case, all models map directly onto SDG 13 ("climate action") and SDG 7 ("clean and affordable energy"). In addition, some models can produce direct estimates of air pollution-related mortality, a key facet of SDG 2 ("health"), whilst most models can produce outputs relevant to agriculture and land use change, informing SDG 15 ("life on land"). The models do not project the impacts of a changing climate, so they are of limited use for adaptation considerations. Some models can take exogenous climate change into account to some extent, either in the form of future restrictions to resources such as bioenergy in a warming climate, or in the form of changing heating and cooling demand.

Each of the models has a strong pedigree and track-record, having been used in a number of projects to understand a range of mitigation and sustainable development-relevant research questions. These questions include the economic impact of mitigation policies, the air pollution and water withdrawal impacts of different mitigation strategies, the potential role for specific technology groups and fuels like carbon capture and storage and bioenergy, and the robustness of different mitigation technology choices under uncertainty around emissions targets.

Work Package 6 will utilise the models' detailed mitigation and sustainable development analysis capabilities to accompany the global integrated assessment and energy models in Work Package 7 ("Model Inter-Comparisons, Global Stocktake & Scientific Assessments"), in order to provide a detailed picture of major and less emitting countries' potential low-carbon pathways and their broader implications. This will allow the co-creation of preferred, robust and feasible mitigation pathways with stakeholders in these countries, which is a key objective of the PARIS REINFORCE project.

The document at hand is the revised version (v1.10R) of deliverable D6.1. The deliverable has been revised with the aim of documenting a roadmap of the WP6 model validation and evaluation steps to be followed in the project (Section 3), as well as of adding the documentation of the additional MUSE-Brazil and TIMES-India models that have been added to the PARIS REINFORCE modelling ensemble.

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Contents

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

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

Table of Figures

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Table of Tables

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Glossary

BtG	Biomass to Gas	**EVs**	Electric Vehicles
BtL	Biomass to Liquids	**FCVs**	Fuel Cell Vehicles
Bio CCS	Biomass with CCS	**GHG**	Greenhouse Gas
CCS	Carbon Capture and Storage	**GtH**	Gas to Hydrogen
CCUS	Carbon Capture, Utilisation and Storage	**HEVs**	Hybrid Electric Vehicles
CH_4	Methane	**IAM**	Integrated Assessment Model
CO_2	Carbon dioxide	**I/O**	Input-Output
CSP	Concentrating Solar Power	**N_2O**	Nitrous Oxide
CtG	Coal to Gas	**NuctH**	Nuclear to Hydrogen
CtH	Coal to Hydrogen	**SDG**	Sustainable Development Goal
CtL	Coal to Liquids	**SSP**	Shared Socioeconomic Pathway
DAC	Direct Air Capture	**PV**	Photovoltaics

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1 Introduction

PARIS REINFORCE will develop and undertake in-depth analysis of national-level decarbonisation pathways for the world's major economies as well as for selected less emitting countries. This includes 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 (the focus of Work Package 5). It also includes national-level analysis for major economies and less developed/emitting countries *outside* Europe (the focus of Work Package 6). This document is a description of the models to be used in Work Package 6.

This document accompanies a detailed, Spreadsheet-based documentation of the different features of the WP6 models and is intended to be a relatively simple (non-technical) and accessible description of the models that can be understood by non-expert stakeholders. The models are:

- **CONTO**: A model detailing the inputs into and outputs from different sectors of the Russian economy, including energy details.
- **GCAM-China**: A region-specific variant of the global, multi-region GCAM integrated assessment model, which details 31 different provinces in China, including flows of energy and goods between them.
- **GCAM-SOUSEI:** A variant of the GCAM integrated assessment model, which has Japan as a specific region and which accounts of uncertainty in estimates of the relationship between CO_2 emissions and temperature change.
- **GCAM-USA:** A region- specific variant of the global, multi-sector GCAM integrated assessment model, which details the energy and goods interaction between all (fifty plus the District of Columbia) USA states.
- **TIMES-India:** A model for India based on the TIMES energy model framework (the precursor to the TIMES framework) representing India as a single region.
- **MAPLE:** A China-specific model based on the TIMES energy modelling framework, which includes a large range of energy technologies.
- **NATEM:** A 23-region TIMES model for North America, including Canada, Mexico and the USA, detailing trade flows and other regional interactions.
- **MUSE-Brazil:** An energy system model for Brazil.
- **TIMES-CAC:** A TIMES model with country-level detail for the Central Asia Caspian region countries Kazakhstan, Uzbekistan, Turkmenistan and Azerbaijan

Table 1.1 details the main features of these models.

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Table 1-1: Details of models to be used in Work Package 6 on non-EU country mitigation analysis

Model	Country / Region	Country Partner	Time horizon	Time step intervals (years)	Sectoral level of representation							
					Upstream	Electricity	Heat	Transport	Buildings	Industry	Agriculture	Land use
CONTO	Russia	IEF-RAS	2040	10	Detailed	Detailed	Detailed	Detailed (road)	Detailed	Detailed	Detailed (energy)	N/a
GCAM-China	China	BC3	2100	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	Detailed
GCAM-SOUSEI	Japan	IGES	2100	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	Detailed
GCAM-USA	USA	BC3	2100	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	Detailed
TIMES-India	India	Grantham	2050	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	N/a
MAPLE	China	CUP	2050	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	N/a
NATEM	USA, Canada, Mexico	IEECP	2050	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	N/a
MUSE-Brazil	Brazil	Grantham	2100	5	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	Basic
TIMES-CAC	Central Asian Caspian	E4SMA	2050	10*	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed	Detailed (energy)	Basic

*Notes: *Flexible to run with shorter time periods*

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1.1 Interlinkages with Deliverable D2.1

Deliverable D2.1 ("Map of models, tools and stakeholder knowledge") summarises all of the key aspects of the models used throughout the PARIS REINFORCE project. D2.1 includes a comprehensive model stocktake, including their geographic coverage, socioeconomic dimensions, sectoral granularity, emissions granularity, policy granularity, SDG granularity and a list of the mitigation and adaptation measures that they represent.

D2.1 is fed from the information included in this deliverable (D6.1) as well as its equivalents covering European models (D5.1) and global models (D7.1). As such, there are clear linkages between these two deliverables, which for the non-European models cover much of the same information. The purpose of D6.1 is to provide a complete and detailed picture of all the models in the non-European modelling Work Package (WP6) of PARIS REINFORCE, whereas D2.1 summarises the entire modelling suite for all regions, including the global models.

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2 What can this range of models explore?

Each of the models to be used in Work Package 6 is intended to allow the development of detailed decarbonisation pathways for major and less emitting economies of the world, encompassed by the relevant model(s). Figure 2.1 shows the different country and regional coverage encompassed by all of the models used in this work package.

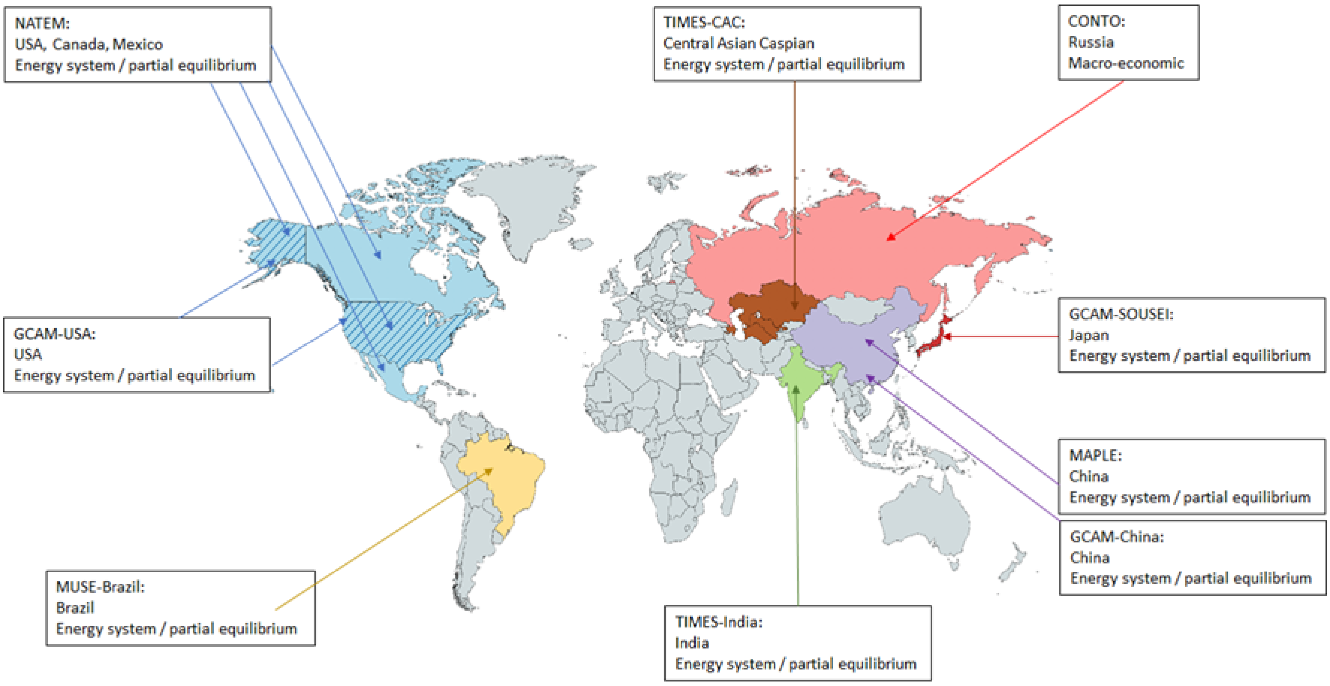

Figure 2-1: Country coverage for the different models

This will enable different stakeholders to provide an informed contribution into the co-design of future scenarios to develop these pathways, as well as engage with the detailed outputs that accompany each modelled pathway. The scenarios and choice mitigation pathways that result will encompass the following attributes:

- Projections for future economic and population growth that drive energy demand as well as demand for other goods and services that result in greenhouse gas (GHG) emissions (e.g. agriculture and land use)
- The technologies and measures available, by what time and to what extent, to allow mitigation
- The costs and performance characteristics of different technologies
- The emissions targets or constraints consistent with different regions' contributions to different long-term, Paris-compliant temperature goals (i.e. well below 2ºC, 1.5ºC)
- The mix of policies that can be implemented to aim to achieve these emissions targets
- The interactions of different resulting mitigation pathways with other policy goals, in particular the sustainable development goals (SDGs) and adaptation goals.

The following sub-sections detail the models' current inputs and assumptions around these factors.

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2.1 Socioeconomic assumptions

Table 2-1: Details of socioeconomic assumptions and how these drive energy demands

Model	Population growth	Economic growth	How these drive energy and other service demand
CONTO	Exogenous	Endogenously calculated through previous years' investments	Industrial and business energy demand driven by output, investment and utilisation of plant capacity. Energy demand of households and road transport driven by income and population, plus assumed energy efficiency improvements.
GCAM-China	Exogenous	Exogenous	Industrial demand grows with GDP, with a decreasing GDP share of industrial output over time. Transport grows (at a decreasing rate) with GDP per capita, and building energy with floor space, linked to GDP per capita, with saturation levels.
GCAM-SOUSEI	Exogenous	Exogenous	Industrial demand grows with GDP, with a decreasing GDP share of industrial output over time. Transport grows (at a decreasing rate) with GDP per capita, and building energy with floor space, linked to GDP per capita, with saturation levels.
GCAM-USA	Exogenous	Exogenous	Industrial demand grows with GDP, with a decreasing GDP share of industrial output over time. Transport grows (at a decreasing rate) with GDP per capita, and building energy with floor space, linked to GDP per capita, with saturation levels.
TIMES-India	Exogenous	Exogenous	Demands for energy in households, buildings, transport and industry related to underlying GDP, sectoral and population growth drivers.
MAPLE	Exogenous	Exogenous	Demands for energy in households, buildings, transport and industry related to underlying GDP, urbanisation and population drivers.
NATEM	Exogenous	Exogenous	Demands for energy in households, buildings, transport and industry related to underlying GDP, sectoral and population growth drivers.
MUSE-Brazil	Exogenous	Exogenous	Industrial demand is an exponential function of population and GDP per capita. Transport demand by mode is a multi-parametric extension of a logistic function of GDP per capita. Demand in households and commercial buildings are logistic functions of GDP per capita.
TIMES-CAC	Exogenous	Exogenous	Demands for energy in households, buildings, transport and industry related to underlying GDP, sectoral and population growth drivers.

In the case of each model, because the assumptions on population are exogenous to the model, they can be

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changed, to reflect underlying scenarios such as those of the Shared Socioeconomic Pathways (SSPs).

Similarly, in all models except the Russian region's CONTO model, economic growth (either as absolute GDP growth, or GDP per capita growth, depending on the model in question) assumptions can be adjusted to reflect SSPs or alternative scenario input choices. In the case of CONTO, the GDP growth path is determined endogenously (i.e. within the model's own calculations, as opposed to coming from an exogenous input assumption). This is done through linking investment in sectors from previous years to the growth of those sectors in future years, simulating the real-world process of economic growth. As such, different mitigation scenarios will endogenously lead to different patterns of input into, output from, and investment in different sectors of the Russian economy, thereby determining different economic growth paths.

In the case of all models, there is a functional relationship between the growth in the underlying drivers for energy demand in the transport, industrial and building sectors (such as GDP, or GDP per capita) and changes in the demand for energy services such as industrial heat, transport and building services (heating, cooling, lighting, appliances). In most cases, this relationship reflects that as the underlying driver increases, the energy demand also increases, but tends to do so at a slower—and decreasing—rate, to reflect the fact that there is a decreasing demand for additional energy services as incomes rise. In other words, the *income elasticity of energy demand* tends to be less than one, which means that a 1% increase in income leads to a <1% increase in a particular energy service, and furthermore this income elasticity tends to reduce over time. Some models (in particular the three regional GCAM models) explicitly represent energy service demand saturation levels in the building sector, reflecting ultimate limits to factors such as building floor space. In such cases, the income elasticity of building energy service demands falls to zero.

In addition to these assumptions on the decreasing rate of demand for energy services with increasing incomes, the CONTO model, GCAM models and /TIMES-based models (TIMES-India, MAPLE, NATEM and TIMES-CAC) also represent the fact that as energy prices rise (for example owing to carbon prices and/or the substitution of more expensive energy technologies for less expensive ones) the demand for energy services falls accordingly, reflecting the notion of energy *price elasticity of energy demand*.

The combined impact of income and price elasticity of energy demand can capture (to some extent) behavioural changes in terms of the take-up of more efficient modes of travel and changes in behaviour around the use of lighting, cooling, heating and appliances in buildings. However, more profound behavioural changes, such as large-scale shifts from private motorised transport to public transport and/or active transport (i.e. walking and cycling) are not captured in these models. As such, any scenarios that assume policies to implement and support such shifts are most likely to be implemented through exogenous input assumptions.

Finally, it should be noted that, , the details outlined in Table 2.1 concern only energy demand. The GCAM models also represent the evolution of demand for agricultural and land use services over time, with related greenhouse gas emissions. In these models' cases, the demand for such services is driven by underlying socioeconomic drivers in the same way as for energy services. Further details are given in the full documentation of the GCAM model (see D7.1).

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2.2 Mitigation technologies and measures included in each model

Table 2-2: Details of mitigation measures (energy supply processes involving low-carbon fuels)

	CONTO	GCAM-China	GCAM-SOUSEI	GCAM-USA	TIMES-India	MAPLE	NATEM	MUSE-Brazil	TIMES-CAC
Upstream	**H2:** GtH CCS CtH CCS Electrol	**Synfuels:** CtL CCS BtL BtL CCS **H2:** GtH CCS CtH CCS Electrol NuctH	**Synfuels:** CtL CCS BtL BtL CCS **H2:** GtH CCS CtH CCS Electrol NuctH	**Synfuels:** CtL CCS BtL BtL CCS **H2:** GtH CCS CtH CCS Electrol NuctH	**H2:** GtH CCS CtH CCS Electrol	**Synfuels:** CtG BtG **H2:**	**Synfuels:** BtG BtL BtL CCS GtL CCS **H2:** Electrol	**Synfuels:** BtG BtL BtL CCS GtL CCS **H2:** GtH GtH- CCS Electrol	**Synfuels:** CtG CtL BtG **H2:** Electrol
Heat	Geo Biomass	Biomass	Biomass	Biomass	Biomass (in CHP)	Coal CCS Biomass	Coal CCS Gas CCS Oil CCS Geo Biomass Bio CCS	Biomass (in CHP)	Biomass
Electricity	Nuc (fis) Nuc (fus) Hydro Biomass Geo Solar PV Wind	Coal CCS Gas CCS Nuc (fis) Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind	Coal CCS Gas CCS Nuc (fis) Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind	Coal CCS Gas CCS Nuc (fis) Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind	Coal CCS Gas CCS Nuc (fis) Hydro Biomass Bioccs Geo Solar PV Solar CSP Wind	Coal CCS Gas CCS Nuc (fis) Nuc (fus) Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind	Coal CCS Gas CCS Nuc (fis) Nuc (fus) Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind Tidal Marine	Coal CCS Gas CCS Nuc (fis) Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind	Coal CCS Gas CCS Hydro Biomass Bio CCS Geo Solar PV Solar CSP Wind

Notes: Upstream sector technologies as follows: CtL CCS = Coal to Liquids with Carbon Capture and Storage (CCS); CtG CCS = Coal to Gas with CCS; GtL CCS = Gas to Liquids with CCS; BtG = Biomass to Gas; BtL = Biomass to Liquids; BtL CCS = Biomass to Liquids with CCS; GtH CCS = Gas to Hydrogen with CCS; CtH CCS = Coal to Hydrogen with CCS; Electrol = Electrolyis; NuctH = Nuclear to Hydrogen; Geo = Geothermal; Bio CCS = Biomass with CCS, Nuc (fis) = Nuclear fission; Nuc (fus) = Nuclear fusion; Solar CSP = Concentrating Solar Power.

Of the technologies and sectors shown in Table 2.2, there is most variation in the different "Upstream" energy conversion processes included in the models. These are very region-specific, and include processes such as the conversion of solid fossil fuels (coal) into liquids (oil), a key strategic process for some regions which are heavily oil import-dependent. Mitigation technologies include adding carbon capture and storage (CCS) to these processes, as well as substituting biomass for coal or gas. Hydrogen is itself a zero-carbon fuel which can be used in transport and heating. But some processes to produce it (specifically, from coal and gas, when combined with water), result in CO_2 emissions. Hence, low-carbon ways of producing hydrogen include the use of CCS, as well as electrolysis (provided the electricity that splits the water into hydrogen and oxygen is from low-carbon sources), and finally the high-temperature splitting of water into hydrogen and oxygen using heat from nuclear power generation.

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Table 2-3: Details of mitigation measures (energy demand processes involving low-carbon fuels)

	CONTO	GCAM-China	GCAM-SOUSEI	GCAM-USA	TIMES-India	MAPLE	NATEM	MUSE-Brazil	TIMES-CAC
Industry	Gas Biomass Electricity Efficiency	Gas Hydrogen Biomass Electricity	Gas Hydrogen Biomass Electricity	Gas Hydrogen Biomass Electricity	Gas Biomass Electricity	Gas Biomass Electricity	Gas Hydrogen Biomass Electricity CCS	Gas Hydrogen Biomass Electricity CCS	Gas Hydrogen Biomass Electricity CCS
Transport (road)	Gas EVs FCVs Efficiency	Gas HEVs EVs FCVs Biofuels	Gas HEVs EVs FCVs Biofuels	Gas HEVs EVs FCVs Biofuels	Gas HEVs EVs FCVs Biofuels Efficiency	Gas HEVs EVs Emission standards Efficiency	Gas HEVs EVs FCVs Biofuels Efficiency	Gas HEVs EVs FCVs Biofuels Efficiency	Gas HEVs EVs FCVs Biofuels Efficiency
Transport (rail)		Electricity Efficiency	Electricity Efficiency	Electricity Efficiency	Electricity Efficiency	Electricity	Electricity Hydrogen Efficiency	Electricity Hydrogen Efficiency	Electricity
Transport (air)		Biofuels	Biofuels	Biofuels	Biofuels Efficiency	Biofuels	Biofuels Efficiency	Biofuels Electricity Efficiency	Biofuels
Transport (marine)		Biofuels	Biofuels	Biofuels	Biofuels Efficiency		Gas Hydrogen Biofuels Efficiency	Gas Hydrogen Biofuels Efficiency	
Buildings (heating)	Electricity Efficiency	Gas Biofuels Electricity	Gas Biofuels Electricity	Gas Biofuels Electricity	Gas Biomass Electricity Efficiency	Gas Electricity Efficiency	Gas Hydrogen Biofuels Electricity Efficiency	Gas Hydrogen Biomass Electricity Efficiency	Gas Electricity Efficiency
Buildings (lighting, appliances, cooling)	Efficiency				Efficiency	Efficiency	Efficiency	Efficiency	Efficiency
Agriculture (energy)							Biomass Electricity	Biomass Electricity	

Notes: EVs = Electric Vehicles; FCVs = Fuel Cell Vehicles, HEVs = Hybrid Electric Vehicles

As shown in Table 2.3, although there variation between the demand-side mitigation technologies that can be represented in the different models, most models have a technology-rich representation of mitigation options in each sector. In addition, the models can in principle be updated so as to represent additional technologies. For example the global TIMES Integrated Assessment Model (see details in D7.1) was recently updated to represent Direct Air Capture of CO_2 (DAC)[1]. All MARKAL-TIMES models could in principle be updated in this way. Finally, a

[1] Realmonte et al (2019) An inter-model assessment of the role of direct air capture in deep mitigation pathways. In: Nat Comms 10 (1), S. 3277. DOI: 10.1038/s41467-019-10842-5.

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number of the models can be used to simulate behaviour changes such as demand reductions in particular sectors (e.g. transport, as a result of modal shifts, or buildings, as a result of changes to thermostat heating / cooling settings). So Table 2.3 is primarily a description of mitigation *technologies*.

2.3 Policies included in the models

Table 2-4: Details of mitigation-relevant policies

Measure	CONTO	GCAM-China	GCAM-SOUSEI	GCAM-USA	TIMES-India	MAPLE	NATEM	MUSE-Brazil	TIMES-CAC
Emissions targets	✓	✓	✓	✓	✓	✓	✓	✓	✓
Carbon tax	✓	✓	✓	✓	✓	✓	✓	✓	✓
Product bans / regulations		✓	✓	✓	✓	✓	✓	✓	✓
Energy mix targets	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy efficiency targets	✓	✓	✓	✓	✓	✓	✓	✓	✓
Subsidies/ finance for techs	✓	✓	✓	✓	✓	✓	✓	✓	✓
Border carbon tax	✓						✓		✓

All models can include carbon pricing/taxation and CO_2 emissions constraints as key policy instruments to change the pattern of energy technology take-up, thereby simulating mitigation. All models can also represent subsidies for low-carbon technologies, since each considers the costs of these technologies, as well as energy technology portfolio mix targets and energy efficiency targets.

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2.4 Analysis of other implications (SDGs and adaptation)

Table 2-5: Details of SDGs (other than SDG13: climate action) measures that can be analysed

Measure	CONTO	GCAM-China	GCAM-SOUSEI	GCAM-USA	TIMES-India	MAPLE	NATEM	MUSE-Brazil	TIMES-CAC
§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							✓		
§12: Responsible production & consumption		✓	✓	✓			✓		
§14: Life below water									
§15: Life on land		✓	✓	✓			✓	✓	✓
§16: Peace, Justice and institutions									

Table 2.5 details those SDG measures that the documented models can inform *directly* from their outputs. For example, all of the models track biofuels and fossil fuel use, from which estimates of particulate matter and thereby respiratory health impacts (a key metric for SDG 3) can be estimated. However, only the GCAM models and the MAPLE model actually include outputs that directly inform SDG 3. In the case of the GCAM models, the relevant metric is mortality resulting from air pollutants, whilst in the case of MAPLE it is an evaluation of health damage based on mortality, as derived from air pollutant emissions.

There are many other SDG dimensions that can be addressed by using relevant outputs from the models. For

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example, each model produces outputs on the quantity of nuclear power deployed, which can support the investigation of non-proliferation issues relevant to the "Peace" element of SDG 16. In addition, changes in energy costs/prices as calculated by the models are not only directly relevant to SDG 7, but also indirectly to SDG 1 if interpreted as a driver of poverty.

Table 2.5 does not indicate the degree of detail with which different SDG-relevant metrics are produced by the different models. This is because each SDG has several metrics and sub-metrics, which are influenced by a range of factors. For example, whilst many models can input into SDG 15, this is in many cases through the use of a simplified representation of afforestation and land use changes, which may mask, or at least not consider, a range of other determinants affecting the quality of life on land. A fuller description of each model's consideration of different SDG implications is shown in the detailed documentation for each model, in Section 4.

The models listed above do not in general produce outputs that are directly relevant to adaptation considerations but can offer indirect insights to inform adaptation planning. The GCAM models have 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. The TIMES-CAC model allows for water use restrictions to be imposed for Kazakhstan (with the ability to replicate this for the other three countries that it represents), as well as calculating additional building cooling requirements.

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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2.5 How does each model calculate a mitigation pathway?

There are three different families of energy system models in WP6:

- The -TIMES models (MAPLE, TIMES-India, NATEM, and TIMES-CAC). These models all operate on a "perfect foresight cost-optimisation" principle, whereby the total energy system cost is minimised over the model simulation time horizon. This energy system cost consists of primary fossil fuel, biomass and uranium costs. It also includes the capital and operational costs of the energy supply technologies (e.g. power plants, heat generators, synthetic fuel production plants) and energy demand technologies (e.g. cars, light bulbs, heaters) that use these fuels (plus other, freely available energy resources such as wind, water and sunlight) either directly or after they have been converted into usable forms. This cost minimisation is calculated so as not to breach any imposed limits or constraints, such as for the annual deployment rate of specified energy technologies, or for the total emissions limit imposed. The "perfect foresight" aspect of these models means that *all* consequences of technology deployments, fuel extraction and energy price changes over the entire time horizon are considered in the cost-optimisation calculation.
- The GCAM models (GCAM-China, GCAM-USA, and GCAM-SOUSEI). These models use a "recursive dynamic optimisation" principle. This means that the models do not consider all future time periods in the optimisation calculation. After the models solve for the least-cost energy system in a given period, they then move to the next time period and perform the same exercise. This is a marked contrast to perfect foresight optimisation models, which consider all future time periods when performing the optimisation calculation. 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.
- The CONTO model. In contrast to the above models, for which economic growth assumptions are exogenous, the CONTO model produces its own economic forecast, which like many other economic models, seeks to maximise economy-wide "welfare" (broadly defined as the profits of producers and the utility of consumers) and achieve an "equilibrium" between the supply of and demand for all goods and services in the Russian economy in a given time period represented. The model then moves to the next time period, representing economic growth by tracking investments and improvements in productivity over time. It tracks energy use from different fuels in the different economic sectors, as well as the household sector. It can represent mitigation of climate change (i.e. emissions reductions, through the substitution of low-carbon for high-carbon fuels) through the changing relative prices of low-carbon versus high-carbon fuels in each sector, in response for example to carbon taxes or subsidies for low-carbon fuels and technologies.
- The MUSE-Brazil model applies a "recursive dynamic" approach to the modelling of a mitigation pathway. Accordingly, the carbon budget is allocated to each one of the simulated time periods and the model solves period by period using a limited foresight approach which reduces the knowledge of future energy market demand and prices to a selected number of years belonging to the foresight period. In each period, the model performs an agent-based simulation of each energy sector, whose principles impose that agents should perform investments according to their objectives. The agent-based structure is harmonized through a market clearing algorithm which balances supply and demand of energy commodities and converges using limited foresight on prices. As mentioned for the GCAM models, the recursive dynamic approach is a marked contrast to perfect foresight optimisation models, which consider all future time periods when performing the optimisation calculation.

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2.6 Example use cases for each model

Table 2-6: Key examples of policy-relevant questions addressed by each model in recent years

Model	Example study	Research question/focus	Selected key findings
CONTO	Shirov and Kolpakov (2019)	Macroeconomic impact of the energy technologies changes in Russia: Input-Output approach	Under a 1.5ºC scenario the Russian economy may lose 0.5 percent points of annual growth as a result of mitigation measures. The dependence on imports is a crucial constraint on mitigation.
GCAM-China	Yu et al. (2019)	Carbon capture, utilisation and storage (CCUS) in China's mitigation strategy: insights from integrated assessment modelling	Across provinces and development pathways, early deployment of CCUS occurs within industrial and synthetic fuel production sectors, followed by increased deployment in the power sector by mid-century. Storage resource availability is unlikely to constrain CCUS.
GCAM-SOUSEI	Silva Herran et al. (2019)	Global energy system transformations in mitigation scenarios considering climate uncertainties	Even when climate uncertainties are reflected at different scales across energy supply components, achieving mitigation targets needs partial decarbonisation of supply, scaling up of carbon capture and storage (CCS), and decreased energy consumption.
GCAM-USA	Ou et al. (2018)	Environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution	Renewables low-carbon pathways require less water withdrawal and consumption than nuclear and carbon capture pathways, but produce higher particulate matter-related mortality costs due to use of biomass in residential heating.
Times-India	Koberle et al. (2020)	Energy transition in India in the next decade	India's coal sector is expected to face mounting challenges and transition due to the increased competitiveness of solar and wind, independent of any increases in climate policy ambition.
MAPLE	Deep Decarbonisation Pathways Project (2019)	Key facets of decarbonisation of China in line with limiting global warming to 2°C	Chinese CO_2 emissions reduce to 4.8 Gt in 2050, 34% lower than 2010, mainly due to reduced CO_2 emissions from industry and power generation.
NATEM	Vaillancourt et al. (2018a)	The role of bioenergy in low-carbon energy transition scenarios in Quebec (Canada).	Much higher penetration of bioenergy is feasible compared to the pathway proposed by the government of Quebec in its 2030 energy policy to achieve the GHG mitigation target.
MUSE-Brazil	Kerdan, I.G. et al. (2019)	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 GtCO2 by 2050 through reforestation. In this scenario, the capital investment in carbon sequestration and storage would be substantially reduced.

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TIMES-CAC	Kerimray et al. (2018).	Long-term climate change mitigation pathways in Kazakhstan in a post Paris Agreement context.	A 25% GHG emissions reduction pathway (in line with the NDC) is ambitious compared with current energy policies and mitigation actions, and would require an almost full phase-out of coal consumption in power generation by 2050.

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3 Model validation

Regarding the use of models such as those included in WP6 (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.

In spite of 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 3.1, 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 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 WP6 is the series of regional stakeholder workshops 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 same/similar regions 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 scenarios, and why the models respond in the way that they do.

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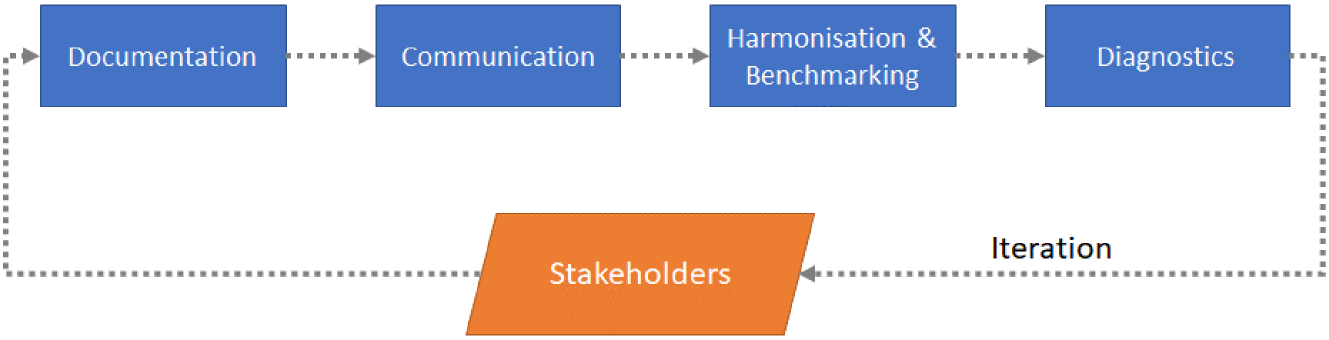

Figure 3-1: Model validation process in PARIS REINFORCE

3.1 Model Validation references

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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*.

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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 constant for ease of reference, and comprises the following sections:

1. Short model overview
2. Key features of the model (including energy system representation, time horizon, regions covered)
3. Emissions covered and climate module (if relevant)
4. Drivers of energy and other GHG-emitting service demands
5. Model calibration
6. Main mitigation measures
7. Rationale for model solution
8. Key policy questions that can be addressed
9. SDG, adaptation and other implications that can be calculated
10. Recent use-cases
11. References

The model descriptions have been ordered alphabetically.

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4.1 CONTO

4.1.1 Overview

CONTO is a system of interconnected macro-structural calculations at the national level, which allows it to describe the synchronised development of economy and the energy sector of the Russian Federation, as well as the level of associated CO_2 emissions. The economic unit is represented by input-output tables, which describe the inter-industry goods flows during production and consumption processes. The energy sector is described in detail in the form of energy balances corresponding to the methodology of the International Energy Agency (IEA). The modelling approach is elaborated in such a way that indicators of socioeconomic development affect the volume and efficiency of energy consumption in the country, which, in turn, determine the economic dynamics of industries involved in the technological chain of energy supply. CONTO also includes the optimisation unit for evaluating the effective fuel structure in the transportation and power sectors based on the cost characteristics of competing technologies. CO_2 emissions are calculated in connection with economic input-output tables. This logical framework is well suited to simulating emissions mitigation by both economically and through regulations stimulating energy efficiency and structural change in the fuel mix. Estimation of the macroeconomic impacts of the application of climate-related measures is a substantial component of the modelling process. CONTO is designed specifically for this task formulation, although it is rather flexible for a wide range of research issues for the economy-energy-emissions triangle and can be expanded during the implementation of the PARIS REINFORCE project to take into account potentially appropriate emission mitigation practices.

4.1.2 Key features of the CONTO model

4.1.2.1 Economic activities coverage

The statistical base of the CONTO model is a series of input-output (I/O) tables for Russia at current and constant prices for 1980–2015, which are consistent with the official data of the Russian Federal State Statistics Service (Rosstat), including the System of National Accounts (SNA). There are 44 economic activities in the I/O tables of CONTO shown in Table 4.1.

Table 4-1: Economic activities nomenclature in CONTO

Sector detailed in CONTO model	
Agriculture	Medical, optical, and precision instruments
Petroleum extraction	Automobiles, highway transport equipment
Natural gas extraction	Sea transport equipment and its repair
Coal mining	Airplanes, rockets, and repair
Other Fuels, incl. Nuclear	Railroad equipment and its repair
Ores and other mining	Recycling
Food, beverages, tobacco	Electric, gas, and water utilities
Textiles, apparel, leather	Construction
Wood and wood products	Wholesale and retail trade
Paper and printing	Hotels and restaurants
Petroleum refining	Transport and storage
Chemicals	Communication
Pharmaceuticals	Finance and insurance
Plastic products	Real estate
Stone, Clay, and Glass products	Equipment rental
Ferrous metals	Computing service
Non-ferrous metals	Research and development
Fabricated metal products	Other business services
Machinery	Government, defense, social insurance
Computers, office machinery	Education
Electical apparatus	Health services
Radio, television, communication equipment	Other social and personal services

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4.1.2.2 Energy sectoral detail

The Russian energy sector is described in the form of energy balances corresponding to the methodology of IEA. The energy balance primary includes coal, natural gas, oil, nuclear, hydro, solar, wind, biofuels, and other renewables; and secondary energy resources.

The list of supply and demand categories within energy balance is similar to IEA's methodology with slight simplifications, which are performed in order to synchronise the nomenclature of energy and economy units of CONTO.

Total primary energy supply (TPES) includes production, net exports, bunkers and stock changes.

The final energy consumption unit is very detailed in order to guarantee the maximum coordination with the economic I/O tables. It includes:

- Industry
  - Mining and quarrying
  - Food and tobacco
  - Textile and leather
  - Wood and wood products
  - Paper, pulp and print
  - Chemical and petrochemical
  - Non-metallic minerals
  - Iron and steel
  - Non-ferrous metals
  - Machinery
  - Transport equipment
  - Construction
  - Other industry
- Transport
  - Aviation
  - Road transport
  - Rail transport
  - Other transport
- Residential
- Commercial and public services
- Agriculture, forestry
- Non-energy use in chemical/petrochemical
- Other non-energy use

The final energy consumption indicators of production sectors are directly dependent on their macroeconomic characteristics, which are described in the I/O tables. For instance, natural gas consumption in manufacture of chemicals has the linkage with economic output in this industry, etc. Residential consumption, as with personal transportation, depends on population and incomes.

Secondary consumption includes electricity plants, CHP plants, heat plants, oil refineries, coal transformation, other transformation, energy industry own use and losses.

CONTO provides an optimisation unit that allows to calculate the most cost-effective structure for satisfying the final demand on electricity/heat and transportation. This unit is filled with the technologies for the production of primary and secondary commodities (mining & extractions processes, power plants, etc.) with cost characteristics. Technologies for the production of hydrogen and its use in transport are also put into the optimisation block, although they are not currently used in Russia.

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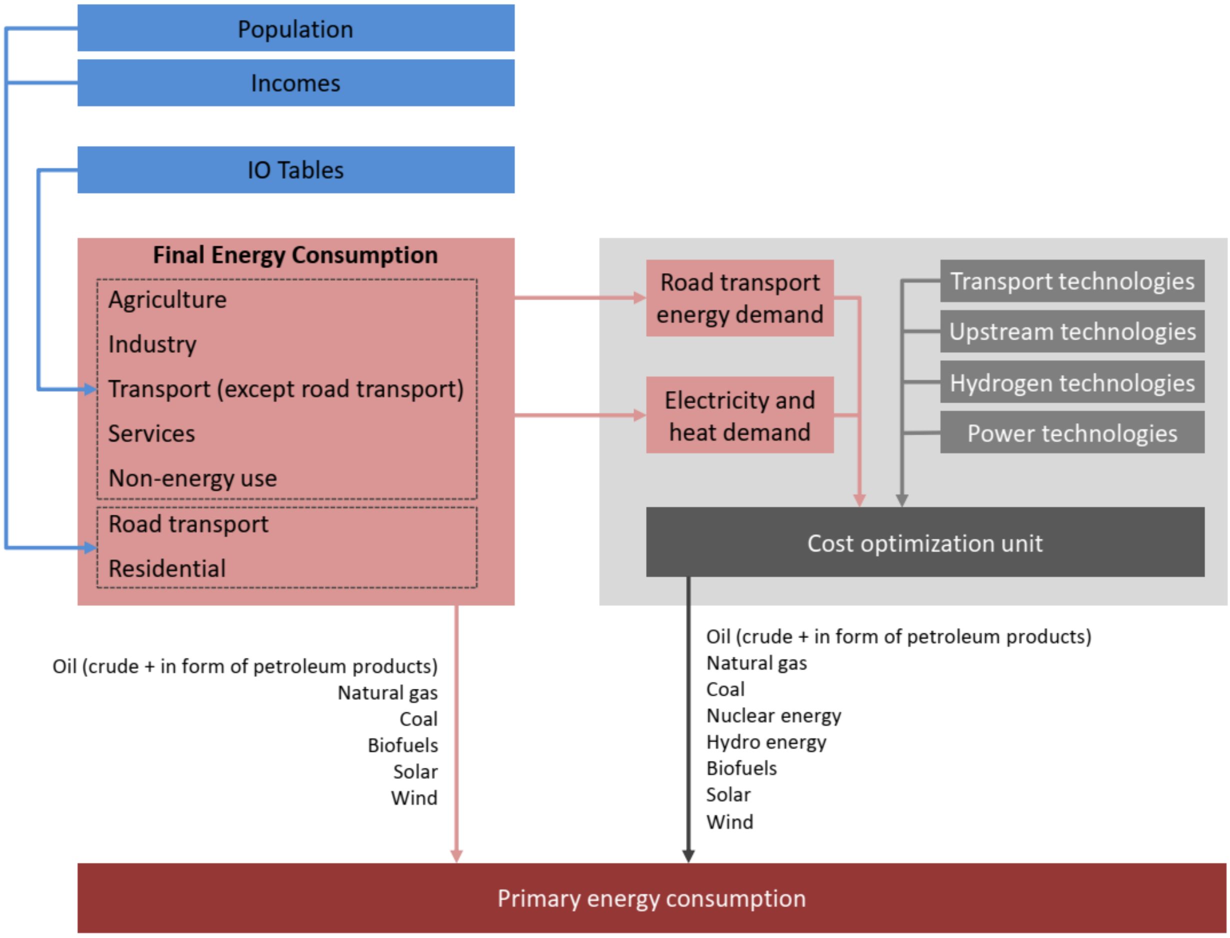

Figure 4-1: Representation of the CONTO energy system

4.1.2.3 Time periods

Currently, the forecast period for the I/O tables, energy balance, and the energy optimisation unit in the CONTO model is 2040. The potential duration of the forecast period is limited only by the quality of scenario indicators. The energy optimisation unit works through ten-year periods (2010, 2020, 2030 and 2040). The I/O tables and the total energy balance are formed for each year.

4.1.3 Climate module & emissions granularity

CONTO is a national-level model that does not have a climate module and that 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.

4.1.4 Drivers of energy and other GHG-emitting service demands

In CONTO, all socioeconomic parameters are endogenous, other than demographic parameters (e.g. population) which are specified exogenously. The model contains a time series of GDP and output for 44 industries, national accounts tables, the balance of income and expenses of the population, indicators of the state budget, balance of payments, balances of the Central Bank and credit organisations, data on sectoral employment, and stocks of fixed capital, etc. All of the above parameters describe the socioeconomic development of the country and affect the processes of energy consumption.

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4.1.5 Calibration of the model

Within CONTO, calibration is performed only for the energy optimisation unit, which estimates the cost-effective fuel mix in the power sector and road transportation sector. The base year is 2010. The main variables to be calibrated include the costs for different technologies; the capacities and utilisation rates; and particular Russian electricity market rules (regarding the supply curve formation). The source of statistical data is IEA's energy balances.

4.1.6 Mitigation/adaptation measures and technologies

CONTO is focused on the implementation of low-carbon solutions in the field of electricity and heat production, and automobile transport. Considerable attention is paid to improving the efficiency of energy consumption through the modernisation of production capacities. 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 CONTO model simulates mitigation. The principal energy sector CO_2 mitigation technology options are as shown in Table 4.2.

Table 4-2: Main CO_2 energy system mitigation options in CONTO

<table>
<tr><th colspan="2">Upstream - Hydrogen production</th><th colspan="2">Electricity generation</th><th colspan="2">Heat generation</th></tr>
<tr><td colspan="2">Electrolysis
Gas to hydrogen
Coal to hydrogen</td><td colspan="2">Efficiency
Nuclear (fission and fusion)
Hydro
Biomass
Geothermal
Solar
Wind</td><td colspan="2">Efficiency
Geothermal
Biomass
Heat pumps</td></tr>
<tr><th colspan="3">Road transport</th><th colspan="3">Other transport</th></tr>
<tr><td colspan="3">Efficiency
Gas vehicles
Electric vehicles
Hydrogen fuel cell vehicles</td><td colspan="3">Gas
Electric
Efficiency</td></tr>
<tr><th colspan="3">Industry</th><th colspan="3">Residential</th></tr>
<tr><td colspan="3">Gas replacing oil / coal
Electricity
Biomass
Efficiency</td><td colspan="3">Efficiency
Electrification</td></tr>
</table>

4.1.7 Economic rationale and model solution

4.1.7.1 Input-output unit

In the economic unit, forecast calculations are carried out in accordance with the input-output methodology. In fact, it is an iterative econometric inter-sectoral model. The concept of the model reflects the logic of a real business cycle.

The iterative calculation procedure begins with an econometric calculation of the dynamics of the elements of final consumption (*Y*), including household consumption, government consumption, investments, changes in inventories, and net exports. Next, output (*X*) is calculated as function of final consumption (*Y*) by solving the basic I/O equation, which also uses a direct cost matrix (*A*) and a diagonal identity matrix (*I*):

$$X = (I - A)^{-1} * Y$$

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Based on the output and investments, the number of employees and the fixed assets by sectors are calculated. Then, the model calculates the value added (*VA*) as a function of output (*X*), which consists of wages, profit, depreciation and taxes:

$$VA^T = X - A^T X$$

At the next step, in accordance with the Leontief price model and based on the elements of value added (*VA*) and output (*X*), the current prices (*P*) are calculated:

$$P = (I - A)^{-1} * VA/X$$

The elements of value added serve as the indicators of incomes of population (wages), business (profit) and government (taxes). These incomes are redistributed into the household consumption, investments and government consumption. Import is a closing element in meeting demand in case of insufficient own capacities (insufficient investment).

This closes the settlement procedure. The process of calculations is repeated until the convergence conditions are met. Once convergence is achieved, the model moves to the next year.

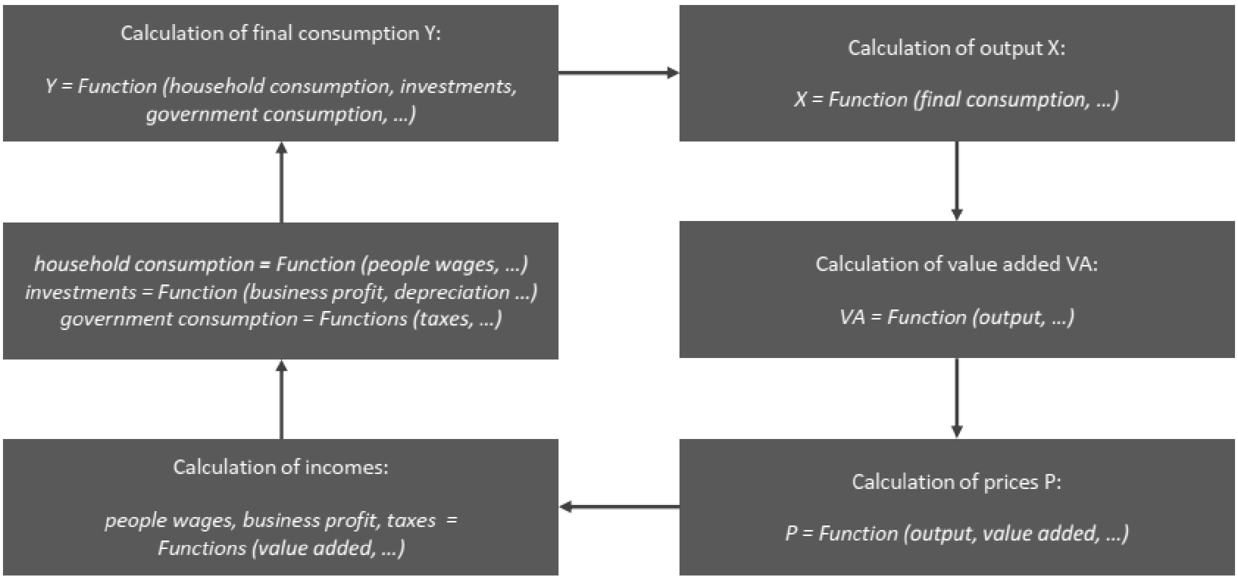

Figure 4-2: The solution algorithm in the economic unit of CONTO

4.1.7.2 Interaction of input-output and energy units

This section describes the energy calculation algorithm in the CONTO model. It notes the interaction of input-output tables and final energy consumption. It is implemented as follows.

Energy consumption in an industry should simultaneously reflect two factors: the gross indicator of the industry and energy efficiency. An industry output can be used as a gross indicator, and energy efficiency is primarily improved through the modernisation of production facilities—that is, through the investment process. In addition, capacity utilisation has an impact. This is important because, firstly, there are economies of scale, and secondly, companies incur conditionally fixed costs.

Thus, final energy consumption (*FC*) is calculated as multiplication of output (*X*) by specific energy consumption

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per output unit (*EFF*), and the latter is the regression function of investment (*INV*) and capacity utilisation (*UTILISATION*) in each industry:

$$FC = X * EFF = X * Function\ (INV,\ UTILISATION)$$

The direct costs matrix (*A*) is in fact a description of the technological structure of the economy. Therefore, its components' (I/O coefficients) dynamics should reflect energy efficiency processes. The CONTO model implements an inverse relationship between energy balance and I/O tables, within which particular I/O coefficients (*a*) regressively depend on *EFF*:

$$a = Function\ (EFF)$$

For example, as a result of investments, production capacities of the ferrous metal industry in Russia are being updated, leading to an increase in the efficiency of natural gas use, which is equivalent to a decrease in the specific consumption of natural gas per unit of output of ferrous metals. This means that the I/O coefficient describing the flow from the natural gas production sector to the ferrous metal production sector should be reduced proportionally.

4.1.7.3 Exogenous parameters of energy efficiency

In the CONTO model, the parameters of fuel consumption on different types of vehicles, fuel consumption in power and heating sectors, and energy efficiency in the residential sector are exogenous.

4.1.7.4 New technologies unit

Currently, a unit of new technologies is being developed. It includes the estimates of the resources and materials use by new and traditional technologies for the production of electricity and road transport. The production of electric vehicles requires less ferrous metals, more non-ferrous metals and electrical equipment (batteries methodologically belong to this category) compared to traditional internal combustion engine (ICE) cars. Solar generation requires significant volumes of metals, concrete and silicon at the investment stage. Wind generation requires significant volumes of concrete, metals, composites and polymers at the investment stage. Therefore, the spread of low-carbon technologies will cause structural transformations in the economy. In the CONTO model, such processes are described through the redistribution of I/O coefficients (*a*).

4.1.7.5 CO_2 emissions unit

CO_2 emissions are calculated based on the output of industries in the I/O tables (*X*) and their specific carbon intensity (*carbon*):

$$CO_2 = X * carbon$$

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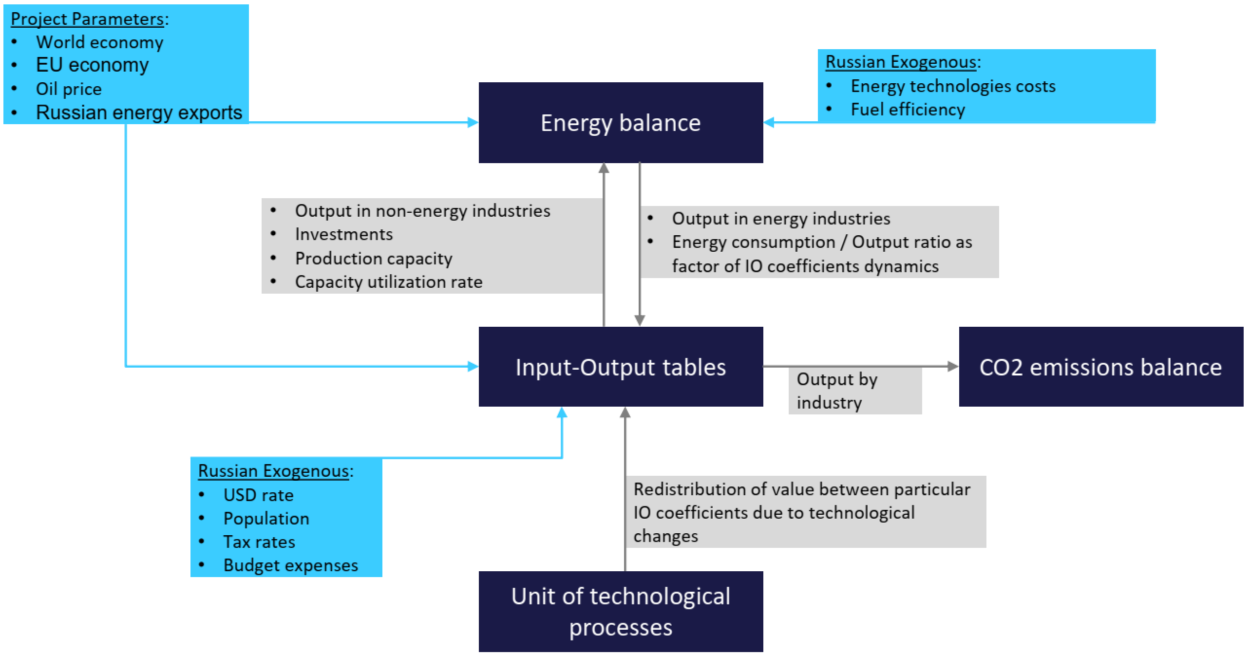

Figure 4-3: CONTO solution algorithm

4.1.8 Key parameters

CONTO pays special attention to the socioeconomic development of Russia. Therefore, in addition to the parameters related to the energy sector, there are indicators which significantly determine the economic dynamics in the country. These arise from the fact that Russia is a key supplier of hydrocarbon fuels to the world market. This leads to high dependence of macroeconomic indicators on the situation in foreign markets, and also increases the role of fiscal policy.

Key economic parameters are:

- demographic data (stabilisation and gradual aging of population);
- oil price (USD) rate (affects income of commodity sectors and dynamics of prices in the economy);
- tax rates (affect business profits and state budget revenues);
- budget expenditures;
- exports of the main products (oil, natural gas and coal); and
- growth rates of the world and the EU economy (affect the exports of Russian products).

Key energy parameters are:

- fuel/energy efficiency;
- energy technology costs; and
- resources of different types of energy.

4.1.9 Policy questions and SDGs

4.1.9.1 Key policies that can be addressed

In Russia, crucial attention is paid to the issue of sparking economic growth after a long recession. That is why the fundamental step in developing national climate policy is to provide the comprehensive scientific knowledge of potential climate-oriented ways to positively affect the economy growth and quality of people’s lives.

In the Russian case study, the key policy-relevant investigations may be focused on searching the trajectories of

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effective decarbonisation of the country that is both in line with its national socioeconomic targets and aligned with a low-carbon world:

- What is the structure of the Russian energy balance, consistent with the Paris Agreement implementation?
- Is there a mix of decarbonisation technologies in the Russian economy that have a neutral/positive effect on socioeconomic development?
- What solutions can have export potential in the low-carbon world?
- What decarbonisation measures can rely heavily on their own production potential?
- What is the impact of emissions mitigation on the price dynamics in Russia?

Key policy measures that can be implemented in CONTO:

- Stimulating the modernisation of production capacities and, consequently, their fuel efficiency (accelerated investments through adjusting business income);
- Subsidies on particular technologies (through adjusting their costs);
- State investment programs in the field of renewable energy, including related production industries;
- CO_2 emissions constraint, carbon tax implementation.

4.1.9.2 Implications for other SDGs

As a national-level model, CONTO is able to assess the qualitative direction of Russia's movement in the field of the sustainable development goals, as detailed in Table 4.3.

Table 4-3: Capability of the CONTO model to assess other SDGs

SDGs	Details
§1. No Poverty	Level of average income, employment rate
§3. Health	Sufficiency of government financing for health care
§4. Quality education	Sufficiency of government financing for education
§7. Affordable and clean energy	Share of low-carbon energy, affordability in terms of price/income ratio

In the case of Russia, these goals may contradict each other, since they will compete for limited financial resources. Therefore, it is possible to evaluate elasticities with which the achievement of one goal can affect the performance of others.

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4.1.10 Recent publications using the CONTO model

Paper	Topic	Key findings
Shirov and Kolpakov (2019)	Macroeconomic impact of the energy technologies changes in Russia: Input-Output approach	Under IPCC's global warming of 1.5 °C scenario, the Russian economy may lose 0.5 percent points of annual growth. The spread of low-carbon technologies is not economically effective yet. Dependence on imports is a crucial constraint.
Shirov et al. (2018)	Macroeconomic impacts of the nuclear energy development (methodology and practical assessment)	Nuclear energy is one of the possible low-carbon solutions. It is rather competitive in Russia. It creates significant inter-industry interactions including at the inter-country level.
Shirov and Kolpakov (2017)	Input-Output approach as an instrument for estimating potential national ecological targets	Having implemented the Paris goals, the Russian economy is able to grow by only 2% which is not enough for solving accumulated structural problems. Initial steps aiming for the modernisation of the Russian economy are needed.
Kolpakov et al. (2017)	Modernisation of industry and high-tech development in the context of "green" growth	The international experience in the development of the green economy is analysed. Common practice shows that green growth is associated with rising prices, accelerating GDP and higher employment. The forced creation of new high-tech industries contributes to economic diversification.
Shirov et al. (2014)	Input-output macroeconomic model as the core of complex forecasting calculations	This paper considers the basic approaches to formation of the up-to-date I/O forecast-analytical tools. It provides a description of key functional relationships in the I/O macroeconomic CONTO model. The paper defines the role of the I/O model in the system of forecasting calculations used at the Institute of Economic Forecasting Russian Academy of Sciences.

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4.1.11 References

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Shirov, A., & Kolpakov, A. (2017). *Input-Output approach as an instrument for estimation of potential national ecological targets*. Paper for 25th IIOA Conference, 2017.

Porfiryev, B.N., Borisov, V.N., Budanov, I.A., Vladimirova, I.L., Dmitriev, A.N., Eliseev, D.O., Kolpakov, A.Yu., Kopylov, A.E., Kuvalin, D.B., Lavrinenko, P.A., Naumova, Yu.V., Semikashev, V.V., Sinyak, Yu.V., Suvorov, N.V., Terentyev, N.E. & Yankov. K.V. (2017). *Modernization of industry and high-tech development in the context of "green" growth.* Monograph / Ed. by Acad. RAS B.N. Porfiryev. Moscow. Scientific Consultant Publ. 2017. 434 p. (In Russian).

Shirov A.A., & Yantovsky A.A. (2014). Input-output macroeconomic model as the core of complex forecasting calculations. *Studies on Russian Economic Development*. *25*(3). 225-234.

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4.2 GCAM-China

4.2.1 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, 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 and 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. See the GCAM description in D7.1 for a full overview of the structure and assumptions in GCAM.

The GCAM model was expanded to include greater spatial detail in the China region, referred to as GCAM-China. GCAM-China is built within the GCAM framework. Hence assumptions in GCAM-China are made in the same way as the rest of the model.

4.2.2 Key features of the GCAM-China model

In GCAM-China, the 31 Chinese provinces are included as explicit regions that operate within the global GCAM model (Figure 4.4). Energy transformation (electricity generation and refined liquids production) and end-use demands (buildings, transportation, and industry) are modelled at the individual province level, and inter-province trade of all energy goods is considered. For electricity trade between provinces, provinces are grouped into 6 grid regions (Figure 4.4). Whereby provinces within the same sub-region can trade freely within that sub-region, trade between regions may be limited. Table 4.4 shows an overview of features calibrated at the country, grid and province level. The model can generate pathways through to 2100 with 5-year time periods.

The more detailed province-level approach for China has advantages over the global version of GCAM, in terms of more detailed assumptions on socioeconomic and energy futures, resulting into potentially more realistic reference scenarios. Also, the higher geographical granularity as advantages for policy analysis and impacts of climate policies might differ strongly between provinces.

Table 4-4: Geographical detail of GCAM-China parameters

Country level (China)	Grid-region level (Figure 1)	Province level
- Fossil fuel reserves, production and prices - Agriculture and land use - Biomass production and prices - International trade in energy commodities	- Final energy prices for electricity - Inter-regional electricity trade	- Renewable energy reserves and usage - Electricity production - Building energy end-use* - Industrial energy end-use - Transportation energy end-use - CCS reserves and usage
**** Building energy end-use by state has a higher detail w.r.t. appliances use than in the global version***		

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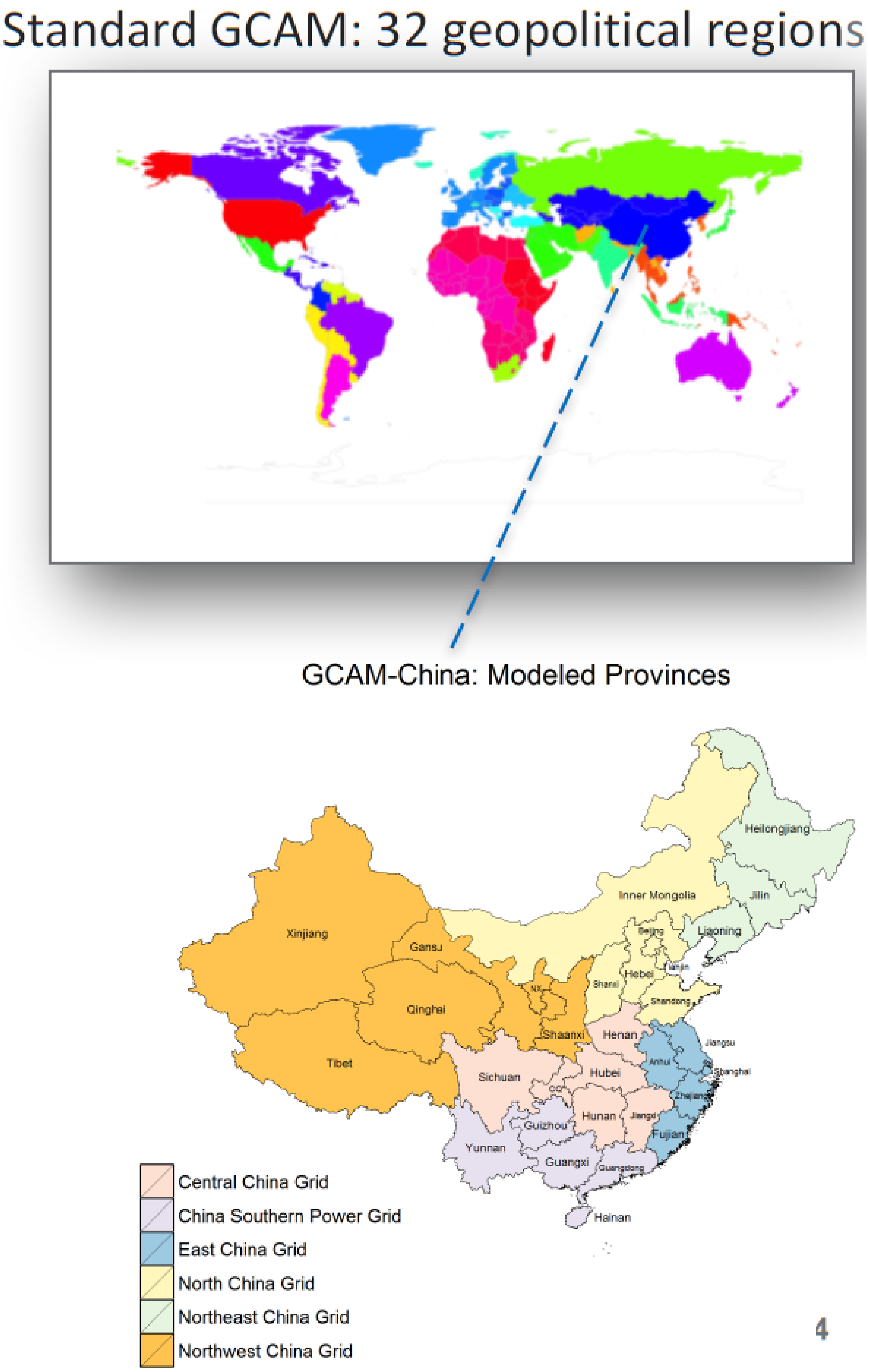

Figure 4-4: Geographical coverage of GCAM-China

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4.2.3 Climate module & emissions granularity

In the main GCAM model, emissions are passed to a climate model called HECTOR, which represents the most critical global-scale earth system processes, as described in detail in the full GCAM model description in D7.1.

4.2.4 Drivers of energy and other GHG-emitting service demands

Economy-wide and sectoral economic growth assumptions, as well as population growth assumptions, drive energy and agricultural sector demand growth, as described in detail in the full GCAM model description in D7.1.

4.2.5 Calibration of the model

The GCAM model is calibrated for its base year, 2010. For international and China-wide data, the same data sources are used for calibration as for the global model, which are predominantly IEA energy balances for energy production and consumption, and FAOSTAT balances for food demand and agriculture. For province- and grid-level data in China (see Table 4.4), national Chinese data sources have been used for calibration.

4.2.6 Mitigation/adaptation measures and technologies

The GCAM-China model has the same range of mitigation and adaptation measures and technologies as available in the full GCAM model, as described in detail in the full GCAM model description in D7.1.

4.2.7 Economic rationale and model solution

The GCAM model operates on a principle of market equilibrium and cost-optimisation to reach equilibrium at least cost in each represented time period, before moving to the next time period, in a so-called recursive dynamic approach, as described in detail in the full GCAM model description in D7.1.

4.2.8 Key parameters

Outcomes in GCAM depend strongly on the assumptions made for socioeconomic, techno-economic, and agronomic parameters. Given the role that GCAM-China might play in the PARIS REINFORCE project, some input parameters will be most relevant for the model outcomes:

- Chinese national GHG reduction target and mitigation burden and other priorities by province
- Province-specific renewable and CCS resources
- Information about under construction/planned/possible energy projects/infrastructures
- Future demand scenarios for energy services by province

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

4.2.9 Policy questions and SDGs

GCAM can be used to explore a range of policies and SDG implications, as described in detail in the full GCAM model description in D7.1.

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4.2.10 Recent publications using GCAM-China

Ref	Title	Key findings
Yu et al. (2019)	CCUS in China's mitigation strategy: insights from integrated assessment modelling	The inclusion of new provincial CO_2 storage cost curves gives a more detailed evaluation of where, in terms of geography and sector, and when CCUS deployment in China may take place. The results suggest that the scale of deployment varies depending on socioeconomic development pathways and the level of deployment of other low-carbon technologies. Across provinces and development pathways, early deployment of CCUS occurs within industrial and synthetic fuel production sectors, followed by increased deployment in the power sector by mid-century. Several provinces, such as Shandong, Inner Mongolia, Hebei, and Henan, emerge as particularly important in CCUS deployment, as a result of large CO_2 point sources and storage availability. Results indicate that storage resource availability is unlikely to constrain CCUS deployment in most provinces through the end of the century.
Yu et al. (2014)	Scenarios of building energy demand for China with a detailed regional representation	The Cold and Hot Summer Cold Winter regions lead in total building energy use. The impact of climate change on heating energy use is more significant than that of cooling energy use in most climate regions. Both rural and urban households will experience fuel switch from fossil fuel to cleaner fuels. Commercial buildings will experience rapid growth in electrification and energy intensity. Improved understanding of Chinese buildings with climate change highlighted in this study help policymakers develop targeted policies and prioritise building energy efficiency measures.

4.2.11 References

Yu, S., Horing, J., Liu, Q., Dahowski, R., Davidson, C., Edmonds, J., & Clarke, L. (2019). CCUS in China's mitigation strategy: insights from integrated assessment modelling. *International Journal of Greenhouse Gas Control*, *84*, 204-218.

Yu, S., Eom, J., Zhou, Y., Evans, M., & Clarke, L. (2014). Scenarios of building energy demand for China with a detailed regional representation. *Energy*, *67*, 284-297.

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4.3 GCAM-SOUSEI

4.3.1 Overview

GCAM-SOUSEI, like the GCAM model from which it is derived, is a multi-region global model, which includes Japan as a separate region. See the GCAM description in D7.1 for a full overview of the structure and assumptions in GCAM.

The level of energy system, agriculture and land use detail for the Japan region allows it to be used to study Japan's national-level low-carbon pathways. In addition, GCAM-SOUSEI uses emission pathways that account for uncertainties in a number of climate-relevant parameters relating CO_2 atmospheric concentrations to global temperature changes.

These emission pathways are obtained from a large set of experimental results with a climate model (Earth system model of intermediate complexity, or EMIC) covering a wider range of parameters and uncertainties than the original GCAM model, leading to a range of CO_2 emissions being associated with each temperature change target.

The climate model in GCAM-SOUSEI emulates the Earth system, covering the range of values of physical and biogeochemical parameters indicated by multiple Earth System Models (ESMs), which are highly complex and detailed models used to analyse the global changes of the atmosphere, the land and the ocean (the original GCAM model includes a simple climate model called the Model for the Assessment of Greenhouse-gas Induced Climate Change, or MAGICC).

The emission pathways for allowable carbon emissions translate into lower total energy consumption, shift from high shares of fossil fuels to larger shares of renewables and nuclear energy, as well as the increase in CCS penetration. Also, larger amounts of bioenergy crops result in conversion of unmanaged land (pastures, arable land among others) into land for bioenergy crops.

4.3.2 Key features of the model

GCAM-SOUSEI combines detailed representations of the energy, land and agricultural systems with a climate model in the same way as for the main GCAM model, as described in detail in the full GCAM model description in D7.1.

The model can generate pathways through to 2100 with 5-year time periods.

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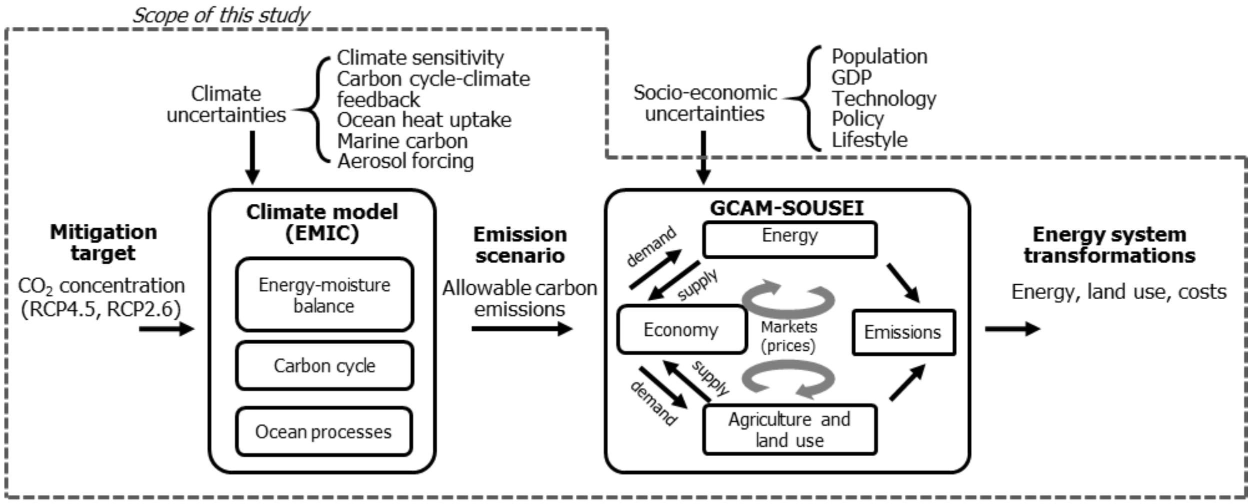

Figure 4-5: Modelling framework illustrating the main components and data flows in the EMIC climate model and GCAM-SOUSEI.

4.3.3 Climate module & emissions granularity

In the main GCAM-SOUSEI model, the EMIC model is used to calculate the climate implications of different emissions levels, as described in Section 4.3.1 and shown in Figure 4.5 above.

4.3.4 Drivers of energy and other GHG-emitting service demands

Economy-wide and sectoral economic growth assumptions, as well as population growth assumptions, drive energy and agricultural sector demand growth, as described in detail in the full GCAM model description in D7.1.

4.3.5 Calibration of the model

Model calibration consists of tuning parameters (such as share weights of energy commodities) so that the values of several socioeconomic indicators (GDP, energy consumption by fuels and sectors, among others) match those of statistics from selected historical periods (1970, 1990, 2005) for the 32 world regions represented in the model.

4.3.6 Mitigation/adaptation measures and technologies

The GCAM-SOUSEI model has the same range of mitigation and adaptation measures and technologies as available in the full GCAM model, as described in detail in the full GCAM model description in D7.1.

4.3.7 Economic rationale and model solution

The GCAM model operates on a principle of market equilibrium and cost-optimisation to reach equilibrium at least cost in each represented time period, before moving to the next time period, in a so-called recursive dynamic approach, as described in detail in the full GCAM model description in D7.1.

4.3.8 Key parameters

The full set of parameters which can be explored and altered in the GCAM-SOUSEI model is detailed in the full GCAM model description in D7.1.

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4.3.9 Policy questions and SDGs

GCAM can be used to explore a range of policies and SDG implications, as described in detail in the full GCAM model description in D7.1.

4.3.10 Recent publications using GCAM-SOUSEI

Ref	Title	Key findings
Silva Herran et al. (2019)	Global energy system transformations in mitigation scenarios considering climate uncertainties	Even when climate uncertainties are reflected at different scales across energy supply components, achieving mitigation targets needs partial decarbonisation of supply, scaling up of carbon capture and storage (CCS), and decreased energy consumption. The effect of climate uncertainties was largest for coal without CCS (up to 100% in 2100 compared to the central scenario) and bioenergy with CCS (up to 23% in 2100 compared to the central scenario). Land for bioenergy feedstocks and the deployment of unmanaged lands for other purposes also had a considerable variation (10-20% in 2100). Compared to the uncertainty in socioeconomic factors quantified in IAMs, the variation induced by the climate uncertainties was small.

4.3.11 References

Silva Herran, D., Tachiiri, K., & Matsumoto, K. I. (2019). Global energy system transformations in mitigation scenarios considering climate uncertainties. *Applied energy, 243,* 119-131

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4.4 GCAM-USA

4.4.1 Overview

The Global Change Assessment Model (GCAM) is a global model that represents both human and Earth system dynamics. It explores the behaviour and interactions between the energy system, agriculture and land use, 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 and 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. See the GCAM description in D7.1 for a full overview of the structure and assumptions in GCAM.

The GCAM model was expanded to include greater spatial detail in the USA region, referred to as GCAM-USA. GCAM-USA is built within the GCAM framework. Hence assumptions in GCAM-USA are made in the same way as the rest of the model.

In GCAM-USA, the 50 U.S. states plus the District of Columbia (hereafter, the 51 states) are included as explicit regions that operate within the global GCAM model (Figure 4.6). Energy transformation (electricity generation and refined liquids production) and end-use demands (buildings, transportation, and industry) are modelled at the individual state level, and inter-state trade of all energy goods is considered. For electricity trade between states, states are grouped into the 13 NEMS Electricity Market Module Regions (EIA 2010), plus Alaska and Hawaii (Figure 4.6). Whereby states within the same sub-region can trade freely within that sub-region, trade between regions may be limited. Also, prices for final energy commodities (except for biomass products) are calibrated per grid region, reflecting regional differences in energy prices. Table 4.6 shows an overview of features calibrated at the country, grid and state level.

4.4.2 Key features of the model

The more detailed state-level approach for the USA has advantages over the global GCAM model, in terms of more detailed assumptions on socioeconomic and energy futures, resulting into potentially more realistic reference scenarios. Also, the higher geographical granularity has advantages for policy analysis, as climate policies often vary by state in the USA, and impacts of climate policies might differ strongly between states.

Table 4-5: Geographical detail of GCAM-USA parameters

Country level (USA)	Grid-region level (Figure 1)	State level
- Fossil fuel reserves and production - Agriculture and land use - Biomass production and prices - International trade in energy commodities	- Final energy prices for electricity, liquids, gas and coal - CCS reserves and usage - Inter-regional electricity trade	- Renewable energy reserves and usage - Electricity production - Building energy end-use* - Industrial energy end-use - Transportation energy end-use
**** Building energy end-use by state has a higher detail w.r.t. appliances use than in the global version***		

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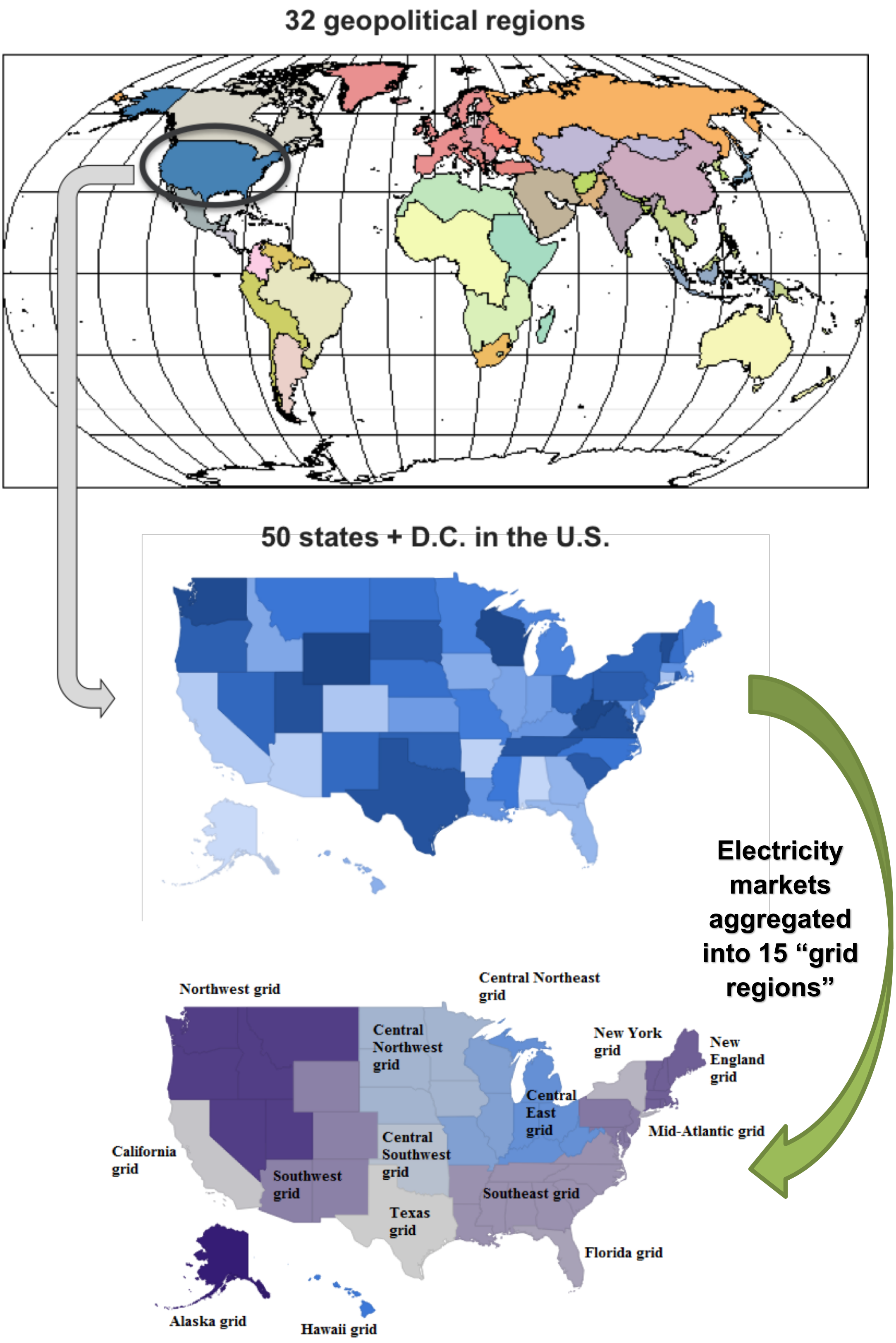

Figure 4-6: Geographical coverage of GCAM-USA

4.4.3 Climate module & emissions granularity

In the main GCAM model, emissions are passed to a climate model called HECTOR, which represents the most

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critical global-scale earth system processes, as described in detail in the full GCAM model description in D7.1.

4.4.4 Drivers of energy and other GHG-emitting service demands

Economy-wide and sectoral economic growth assumptions, as well as population growth assumptions, drive energy and agricultural sector demand growth, as described in detail in the full GCAM model description in D7.1.

4.4.5 Calibration of the model

The GCAM model is calibrated for its base year, 2010. For international and USA-wide data, the same data sources are used for calibration as for the global model, which are predominantly IEA energy balances for energy production and consumption, and FAOSTAT balances for food demand and agriculture. For state- and grid-level data in the USA (see Table 4.5), the State Energy Data System from the EIA (2014) is used as the primary dataset. Socioeconomic data are calibrated for 2015 at the state-level, reflecting data from the U.S. Census Bureau.

4.4.6 Mitigation/adaptation measures and technologies

The GCAM-USA model has the same range of mitigation and adaptation measures and technologies as available in the full GCAM model, as described in detail in the full GCAM model description in D7.1.

4.4.7 Economic rationale and model solution

The GCAM model operates on a principle of market equilibrium and cost-optimisation to reach equilibrium at least cost in each represented time period, before moving to the next time period, in a so-called recursive dynamic approach, as described in detail in the full GCAM model description in D7.1.

4.4.8 Key parameters

Outcomes in GCAM depend strongly on the assumptions made for socioeconomic, techno-economic, and agronomic parameters. Given the role that GCAM-USA might play in the PARIS REINFORCE project, some input parameters will be most relevant for the model outcomes:

- US national/state-level GHG reduction targets and other priorities/plans
- State-specific renewable and CCS resources
- Information about under construction/planned/possible energy projects/infrastructures
- Future demand scenarios for energy services by state

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

4.4.9 Policy questions and SDGs

GCAM can be used to explore a range of policies and SDG implications, as described in detail in the full GCAM model description in D7.1.

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4.4.10 Recent publications using GCAM-USA

Study	Focus	Key findings
Ou et al. (2018)	Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution	Air pollutant emissions, mortality costs attributable to particulate matter smaller than 2.5 µm in diameter, and energy-related water demands are evaluated for 50% and 80% CO_2 reduction targets in 2050. The renewable low-carbon pathways require less water withdrawal and consumption than the nuclear and carbon capture pathways. However, the renewable low-carbon pathways modelled in this study produce higher particulate matter-related mortality costs due to greater use of biomass in residential heating. Environmental co-benefits differ among states because of factors such as existing technology stock, resource availability, and environmental and energy policies.
Iyer et al. (2017)	GCAM-USA Analysis of U.S. Electric Power Sector Transitions	The United States has developed a Mid-Century Strategy to reduce economy-wide greenhouse gas (GHG) emissions to 80% or more below 2005 levels by 2050. Achieving these reductions will entail a major transformation of the energy system, including the electric power sector. The scenarios in this study include substantial decarbonisation of the electric power sector, increased electrification of end-use sectors, and increase in the deployment of low- and zero-carbon technologies such as renewables, nuclear and carbon capture utilisation and storage. The results show that the degree to which the electric power sector will need to decarbonise depends on the nature of technological advances in the energy sector, and the degree to which end-use sectors electrify.
Feijoo et al. (2018)	The future of natural gas infrastructure development in the United states	Existing pipeline infrastructure in the U.S. is insufficient to satisfy the increasing demand for natural gas, and investments in pipeline capacity will be required. However, the geographic distribution of investments within the U.S. is heterogeneous and depends on the capacity of existing infrastructure as well as the magnitude of increase in demand. The results also illustrate the risks of under-utilisation of pipeline capacity, in particular, under a scenario characterised by long-term systemic transitions toward a low-carbon economy. More broadly, this study highlights the value of integrated approaches to facilitate informed decision-making.

4.4.11 References

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4.5 TIMES-India

4.5.1 Overview

TIMES-India model is a bottom-up customised model for the Indian energy and environmental policy context. It is based on a rational expectation hypothesis of inter-temporal optimisation with perfect foresight. The energy service demands are estimated in useful energy terms and supply is met through all energy technologies available currently and forecast for entry in India. The model works out the optimal set of choices based on minimisation of the total discounted system cost of the energy sector under various scenarios. The TIMES-India model is a dynamic LP (linear programming) model of the Indian energy system. It uses LP methods to solve for the technology mix that best meets the specified objectives. It is demand-driven and feasible solutions are obtained only if all specified end-use energy demands are satisfied for every time period. The end-use demands for each sector and for each time period are exogenously estimated. The elements of the model simulate the flow of energy in various forms (energy carriers), from the sources of supply (import, export, mining, and stockpiling) through transformation systems (resource, process, conversion, and demand technologies) to the devices that satisfy the end-use demands.

4.5.2 Key features of the model

In the model, the Indian energy sector is disaggregated into five major energy consuming sectors, namely agriculture, commercial, industry, residential, and transport. Each of these sectors is further disaggregated to reflect the sectoral end-use demands. On the supply side, the model considers various energy resources that are available both domestically and from abroad for meeting various end use demands. These include both the conventional energy sources, such as coal, oil, natural gas, hydropower, and nuclear power, as well as renewable energy sources (RES), such as wind, solar, biomass, and so on. The availability of each of these fuels is represented by constraints in the supply side. The relative energy prices of various forms and sources of fuels dictate the choice of fuels, which play an integral role in capturing inter-fuel and inter-factor substitution within the model.

4.5.3 Time periods

4.5.3.1 Multi-year periods

The model runs over a 35-year period, from 2015 to 2050, at five-year intervals.

4.5.3.2 Intra-year time periods (time slices)

The India-TIMES model has 12 annual time slices, three seasons (summer, winter, spring and autumn), two day and night and two peak slices. Time-slices are especially important to represent the load profile of the power from renewable sources and to assess the implication of electrification of end use sector variable renewable energy deployment.

4.5.4 GHG Emission and local pollutant emissions

In TIMES-INDIA carbon dioxide (CO_2) is considered as the main GHG emission. The other main emissions, including methane (CH_4) and nitrous oxide (N_2O), are expected to be added in the next version.

4.5.5 Calibration of the model

The TIMES-India model is calibrated for its base year, 2015. For calibration, IEA energy balances are used for energy production and consumption.

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4.5.6 Mitigation/adaptation measures and technologies

Table 4-6: Main GHG energy system mitigation options in TIMES-India

Upstream	
Electricity and heat	
Electricity generation	***Heat generation***
Coal with CCS GAS with CCS Nuclear Hydro Biomass (with and without CCS) Solar PV Solar CSP Wind (onshore and offshore)	Coal with / without CCS GAS without CCS Gas with CCS* Biomass
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Hybrid electric vehicles Fully electric vehicles Fuel cell vehicles Emission standards Fuel Economy improvement	Electric high-speed railway
Air	***Marine***
Biofuels in fuel mix Efficiency	Gas Biofuels Efficiency
Buildings (commercial/residential)	
Heating	***Lighting***
Gas replacing coal / oil (coal-to-gas incentives) Electricity replacing coal (coal-to-electricity incentives) Efficiency	Efficiency
Appliances	***Cooling***
Efficiency	Efficiency
Industry	
Chemical	***Non-Metallic***
Caustic soda / soda (efficiency)	Cement/Clinker (low carbon production standard) Cement/Clinker (efficiency) Glass/Paper (efficiency)
Ferrous metal	***Non-Ferrous metal***
Iron and steel with CCS Iron and steel (efficiency of furnace)	/aluminium (efficiency)
Process heat	***Machine drives***
Gas replacing oil / coal Biomass Electricity	Gas replacing oil / coal Electricity
Agriculture	
Energy	***Other***
Biomass and solar	

4.5.7 Economic rationale and model solution

TIMES-India is an LP model that maximises the net total surplus (i.e., the sum of producers' and consumers' surpluses), which is operationally done by minimising the total discounted system cost subject to various constraints like resource, environment, technological or policy constraints. The total system cost includes capital cost, operation and maintenance cost, taxes, subsidies, and revenues from export.

4.5.8 Key Parameters

As a bottom-up technology-rich model, TIMES-India uses the following key parameters as inputs:

- Technical parameters: efficiency, availability factor, lifetime, stock for base year, etc.
- Economic parameters: investment cost, operation fixed cost, variable cost, fuel cost, etc.
- Emission parameters: emission coefficient for fuels and for specific technologies.
- Policy parameters: new technology for starting year, new investment for technologies, technology share

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constraints, emission constraints, carbon tax, etc.

4.5.9 Policy questions and SDGs

The policy questions considered in TIMES-India mainly orient on emissions mitigation and energy policy instruments. Like most bottom-up energy models, multiple kinds of constraints can be added during the energy system optimisation process. The main policy granularity in the model is listed in Table 4.7, with further explanation.

Table 4-7: Main policies simulated in TIMES-India

Emissions mitigation policy instruments	
Tax	***Full.*** Feasible for carbon tax (also other emission tax) constraints for a milestone year.
Emissions target/quota (annual)	***Full.*** Feasible for the annual emission target for CO_2 and local pollutant emissions.
Emissions target/quota (cumulative)	***Partial.*** Possible, provided sufficient historical data.
Regulations (emissions standards, etc.)	***Full.*** Regulations like emission standards for a specific sector or energy commodity. Constraints for carbon emission intensity can also be added.
Energy policy instruments	
Tax	***Full.*** Feasible for taxes set on fuels, technologies, other emissions, etc.
Subsidy	***Full.*** Feasible for subsidy set on energy fuels and technologies; energy service final devices, like gas-oven for coal-to-gas heating policy; and full electric vehicles purchasing behaviour.
Energy mix target	***Full.*** Energy mix targets for both full-economy sector and for specific sector, e.g. electricity generation, transportation, and industry (with sub-sectors).
Efficiency target	***Full.*** Efficiency target mainly for technologies, e.g. power generation efficiency; and fuel-economy standard upgrade for gasoline vehicles.
Regulations (thermal regulation in buildings, banning of diesel cars in urban areas, etc.)	***Full.*** Feasible for regulations for specific sector and energy commodity, e.g. limitation of vehicles with low emission standards in transportation sector, and regulations on low-carbon Ammonia production, etc.

Furthermore, the SDGs considered in the current version model include mainly affordable and clean energy, with details shown in Table 4.8.

Table 4-8: Capability of TIMES-India to assess other SDGs

SDG	**Details**
§7. Affordable and clean energy (e.g., traditional biomass use, %renewable energy)	Cost-effectiveness analysis for clean energy is included in the model framework, also considering the environmental co-benefits.

TIMES-India does not calculate non-climate SDGs directly. However, it is possible to perform "off-model" calculations by soft-linking with the AIM-INDIA CGE model to estimate more SDG implications (SDG7, SDG8, SDG9). For example, the model 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 using employment databases.

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4.5.10 Recent publications

Publication	Topic	Key findings
Koberle et al. (2020)	Energy transition in India in the next decade	India’s coal sector is expected to face mounting challenges and transition due to the increased competitiveness of solar and wind, independent of any increases in climate policy ambition.

4.5.11 References

Koberle, A. C., Shrimali, G., Mittal, S., Jindal, A. & Donovan, C. (2020) Energy in transition: coal, solar, and India’s next decade. The Centre for Climate Finance & Investment, Imperial College Business School

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4.6 MAPLE

4.6.1 Overview

The China-MAPLE model consists of an energy system optimisation module which is based on the TIMES modelling framework. 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). It follows a techno-economic (bottom-up) approach to describe the energy sectors in many details through a variety of specific technologies characterised with their technical and economic parameters. TIMES offers thus a detailed representation of energy sectors, which includes extraction, transformation, distribution, end uses, and trade of various energy forms and materials. TIMES computes an equilibrium on energy markets (partial equilibrium) and determines an optimal configuration of the energy systems to satisfy service demands at a minimum cost over a long-term horizon, while respecting GHG emission limits.

The MAPLE model simulates the investment and operation of major energy technologies under constraints of emissions reductions of GHGs and pollutants in local regions in China. The model can project and simulate future energy use trends in reference scenarios and other comparative scenarios of varying degrees of mitigation action. The calculation objective of the model is that the total cost of the energy system must reach the minimum while exogenously given energy demand and any other major constraints on the energy system (e.g., technology availability and growth rates) are satisfied. The costs include investment costs, residual values of assets, fixed and variable operating costs and maintenance costs, local energy extraction costs, the costs of energy imports beyond China, gains from exports to regions outside of China, major energy transmission and distribution costs, related taxes and additional subsidies.

4.6.2 Key features of the model

4.6.2.1 Energy sectoral detail

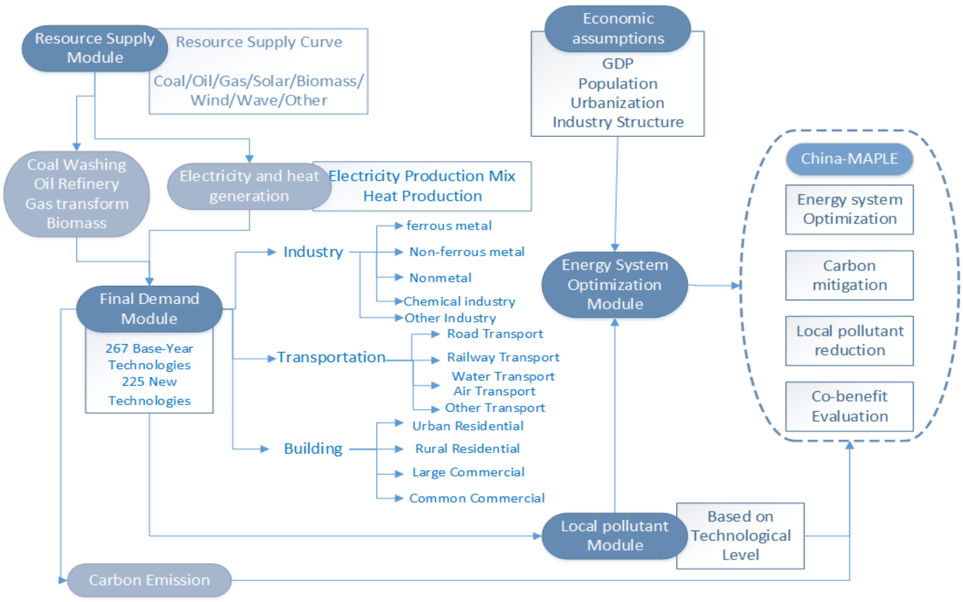

Figure 4-7: Representation of the China-MAPLE energy system for China national-level analysis

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4.6.2.2 Geographic coverage

The MAPLE version 1.0 model has one region (China), i.e. the analysis is based on the national level. In version 2.0, for the residential sector, the geographic granularity of the model includes 31 provinces (regions). That is because the residential sector accounts for a large amount of particulate matter ($PM_{2.5}$) emissions, and MAPLE aims to analyse the co-benefits of emissions reductions for air quality. For the most recent version, more regions have been developed for other sectors, including the residential, electricity, and industrial sectors and sub-sectors.

4.6.2.3 Multi-year time periods

The model performs calculations on five-year steps, from 2010 to 2050, currently being updated to establishing 2015 as the base year.

4.6.2.4 Intra-year time periods (time slices)

When explicitly referring to the electricity sector, it is possible to include intra-annual time slices by season and day-night, to represent the specific variation in electricity supply (such as from time- and weather-dependent renewables like wind and solar photovoltaics) and demand during different typical periods of the day and year (e.g. winter versus summer, day versus night).

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). 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). 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.

4.6.3 GHG Emission and local pollutant emissions

In MAPLE 1.0 and 2.0, carbon dioxide (CO_2) is considered as the main GHG emission. The other main emissions, including methane (CH_4) and nitrous oxide (N_2O), are expected to be added in the next version. For the local pollutant emissions, in version 2.0, sulphur dioxide (SO_2), nitrogen oxides (NO_x), and primary particulate matters are considered as main emissions related to China's air quality improvement.

4.6.4 Drivers of energy and other GHG-emitting service demands

4.6.4.1 GDP, population and urbanisation

The general socioeconomic parameters, including GDP growth rate, population, urbanisation rate, and industry structure, are exogenous. The current socioeconomic modelling assumption is consistent with the model of the World Bank (2012) and other literature. The average annual growth rate of the GDP of China will drop to nearly 6.2% in 2020 and will further decrease to approximately 4% after 2030. The model assumes a population growth scenario in which having a second child is publicly allowed. Based on various sources (Zeng et al., 2013), the model assumes that the total population of China will gradually increase from 1.36 billion in 2010 to 1.433 billion by 2020, peak by 2025-2030, and thereafter decrease to 1.385 billion by 2050. The urbanisation rate of China reached 54.77% in 2014; the rate will reach 58.2% in 2020, 67.1% in 2030, and 75.2% in 2050. These assumptions can be varied in light of updated socioeconomic projection information.

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4.6.4.2 Energy demand drivers

In the TIMES modelling framework, the economic, population and sectoral growths are used to determine specific drivers for the growth in energy demands in reference scenarios with no climate change mitigation policy. For example, the demand for the number of billion kilometre-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. Once the drivers for the different energy demands represented by NATEM 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:

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

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

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

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 incomes.

The TIMES modelling framework also 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, or because fossil-subsidies are reduced, then the demand for energy services could decrease. To do this, TIMES uses another set of inputs, namely the price elasticities of the demands for each energy service considered. The model can then calculate the new demands for these policy cases.

4.6.5 Calibration of the model

Calibration concludes with the base year calibration, which mainly includes the following aspects: (i) total energy consumption and category-based energy consumption of various sectors and sub-sectors; (ii) total energy consumption and category-based energy consumption of third-level sub-sectors; (iii) energy consumption per unit of end-use demand of major divisions; (iv) CO_2 emissions; and (v) emissions of conventional pollutants.

Energy consumption of sub-sectors of the industrial sector is derived on the basis of energy consumption statistics given in the year 2010 (2015 in the updated version in progress) from the Energy Balance Sheet and the Industrial Statistics Yearbook. The energy consumption of the third-level sub-sectors in the industrial sector calculated in the model is summarised according to sub-sectors after calibration on the base year and main statistical data.

The main sources of energy demand data is energy balance tables available from China's energy statistical yearbook. For energy consumption in the industrial sub-sectors and technologies, we used several sources such as China Statistical Yearbook 2006-2011, Industrial Statistical Yearbook 2010-2013, China Steel Statistics 2011, China Chemical Industry Yearbook, China Nonferrous Metals Industry Yearbook, China Energy Statistical Yearbook

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2006-2013. We also use technical parameter documents on production lines of major industrial sectors, as well as calculation and collation from related literature. The data for the transport sector is from *Research into China's Medium and Long-Term Development Strategy on Traffic and Transportation*, *Automotive Energy Outlook 2012*, *China Transport Yearbook*, *China Bulletin on Motor Vehicles Pollution Prevention*, *China Energy Statistical Yearbook 2010-2013*, as well as data research and calculation based on major literature. For the building sector, the data sources include *The Annual Development and Research Report on Building Energy Efficiency in China (2008-2013)*, as well as the summary and calculation of relevant literature.

4.6.6 Mitigation/adaptation measures and technologies

China is on the critical stage of its energy transformation reform and meeting its NDC target for 2030. As a technology-rich model, and like other bottom-up models, mitigation/adaptation measures and technologies can be reflected by constraints for commodities and processes. Referring to the "five-year plan" series, detailed emission standard and mitigation technologies are reported for each sector, especially for final demand sectors.

Demand for end-use energy services is the basis of analysis of the bottom-up energy model. Useful energy provided by end-use energy equipment satisfying demand for end-use energy for the current year is a prerequisite for analysis of energy system optimisation. The demand for end-use energy services pertaining to the Chinese regional model is classified into four major sectors, namely the industrial sector, the transportation sector, the building sector (commercial/residential sector), and the agricultural sector and others, according to segments.

The main mitigation measures and technologies considered in the model are listed in Table 4.9, and the technologies with an asterisk (*) could be further added in the model, based on the requirements of the PARIS REINFORCE project. The main assumptions and technological data will be revised and updated to be consistent with the current updating government database and other modelling groups in the project.

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Table 4-9: Main GHG energy system mitigation options in China-MAPLE

Upstream	
Synthetic fuel production	***Synthetic fuel production***
Coal to gas without CCS Biomass to gas without CCS Coal to gas with CCS* Coal to liquids with CCS*	Coal to gas without CCS Biomass to gas without CCS Coal to gas with CCS* Coal to liquids with CCS* Gas to liquids with CCS*
Electricity and heat	
Electricity generation	***Heat generation***
Coal with CCS GAS with CCS Nuclear Hydro Biomass (with and without CCS) Solar PV Solar CSP Wind (onshore and offshore)	Coal with / without CCS GAS without CCS Gas with CCS* Biomass
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Hybrid electric vehicles Fully electric vehicles *Fully cell vehicles* Emission standards Fuel Economy improvement	Electric high-speed railway
Air	***Marine***
Biofuels in fuel mix Efficiency*	Gas* Biofuels* Efficiency*
Buildings (commercial/residential)	
Heating	***Lighting***
Gas replacing coal / oil (coal-to-gas incentives) Electricity replacing coal (coal-to-electricity incentives) Efficiency	Efficiency
Appliances	***Cooling***
Efficiency	Efficiency
Industry	
Chemical	***Non-Metallic***
Synthetic ammonia (efficiency) Ethylene (efficiency) Yellow phosphorus (efficiency) Caustic soda / soda (efficiency)	Cement/Clinker (low carbon production standard) Cement/Clinker (efficiency) Glass/Paper (efficiency)
Ferrous metal	***Non-Ferrous metal***
Iron and steel with CCS Iron and steel (efficiency of furnace)	Copper/aluminium (efficiency) Zinc/lead (efficiency)
Process heat	***Machine drives***
Gas replacing oil / coal Biomass Electricity	Gas replacing oil / coal Electricity
Steam	***CHP***
Gas replacing oil / coal Electricity	Gas replacing oil / coal Biomass
Agriculture	
Energy	***Other***
Biomass	

The differences between China-MAPLE and other bottom-up models for China is mainly reflected in four aspects:

- China-MAPLE integrates local pollutant control and co-benefit modules into the energy system framework, and models local pollutant emission control measures and technologies in key areas.
- With regard to the local pollutant module, the link between local emissions and energy systems is based on technical rather than activity levels to reflect the mitigation effects of technological advances and structural adjustments. Regarding the benefit evaluation module, it describes the benefits of local pollutants obtained through emissions reduction.
- China-MAPLE introduces energy supply curves in the energy supply module. The supply of coal, oil and

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natural gas includes both domestic production and imports, avoiding deviations caused by fixed energy costs.
- MAPLE model is currently applied in the World Bank Group project on China's energy modelling project, with consideration of linking the bottom-up model with a typical top-down computable general equilibrium approach.

4.6.7 Economic rationale and model solution

TIMES is a dynamic least-cost optimisation model, and as such contains three components: an objective function, variables, and constraints. The first component (objective) corresponds to minimising the net total discounted cost (e.g. 3-5% is typically used in deep decarbonisation studies) of the entire energy system. A single optimisation, which searches for the maximal net total surplus, simulates market equilibrium for each commodity (energy, material, demand). Maximising the net total surplus (i.e. the sum of producers' and consumers' surpluses) is operationally done by minimising the net total cost of the energy system. The second component (variables) corresponds mainly to future investments and activities of technologies at each time period, amount of energy produced or consumed by technologies, as well as energy imports and exports. An additional output of the model is the implicit price (shadow price) of each energy form, material and emission, as well as the reduced cost of each technology (reduction required to make a technology competitive). The third component (constraints) corresponds to various limits (e.g. amount of energy resources available) and obligations (e.g. energy balances throughout the system, useful energy demand satisfaction) to be respected.

The main model assumptions leading to optimal outputs include future technological developments and the structure of energy markets. On the one hand, technological progress is exogenously assumed, and economic agents have a perfect foresight of this. On the other hand, energy markets are assumed to be under perfect competition. Moreover, TIMES considers only energy markets, and thus equilibrium is not assumed for all markets in the economy. From that perspective, TIMES computes only a partial equilibrium on energy markets.

4.6.8 Key Parameters

China is a country with a large difference in energy production and consumption technologies among provinces. As a bottom-up technology-rich model, a large number of data and parameter collection processes are required. The main parameters include:

- Technical parameters: efficiency, availability factor, lifetime, stock for base year, etc.
- Economic parameters: investment cost, operation fixed cost, variable cost, fuel cost, etc.
- Emission parameters: emission coefficient for fuels and for specific technologies.
- Policy parameters: new technology for starting year, new investment for technologies, technology share constraints, emission constraints, carbon tax, etc.

Taking the technical parameters of the power sector as an example, power generation technologies mainly include thermal, nuclear and renewable energy power generation technologies. Coal power and natural-gas-based power generation constitutes the main technology of thermal power generation in China. With regard to technical parameters of three typical coal-fired units, power production efficiency of the supercritical unit is approximately 41-42%, coal consumption per unit of power generation being about 310 grams of coal equivalent (gce)/kWh, and that of the ultra-supercritical unit is 45%-47%, coal consumption per unit of power generation standing at about 280 gce/kWh. The natural gas power generation technology in the base year is mainly natural gas-based gas turbine technology and gas-steam combined cycle units. Natural gas in China has the merits of higher efficiency, relatively environmental protection, smaller floor area and shorter construction period compared with coal-fired power generation. Because construction and operating costs of nuclear power plants are relatively high (about three times that of thermal power plants), its power generation cost is higher (about 0.42-0.54 Yuan/kWh

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on average). Furthermore, power generation technologies involving wind power, solar energy, biomass, small hydropower and other sorts of renewable energy also play an important role in China's power production.

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

4.6.9 Policy questions and SDGs

The policy questions considered in MAPLE mainly orient on emission mitigation and energy policy instruments. Like most bottom-up energy models, multiple kinds of constraints can be added during the energy system optimisation process. The main policy granularity in the model is listed in Table 4.10, with further explanation.

Table 4-10: Main policies simulated in China-MAPLE

Emissions mitigation policy instruments	
Tax	***Full.*** Feasible for carbon tax (also other emission tax) constraints for a milestone year.
Emissions target/quota (annual)	***Full.*** Feasible for the annual emission target for CO_2 and local pollutant emissions.
Emissions target/quota (cumulative)	***Partial.*** Possible, provided sufficient historical data.
Regulations (emissions standards, etc.)	***Full.*** Regulations like emission standards for a specific sector or energy commodity. Constraints for carbon emission intensity can also be added.
Energy policy instruments	
Tax	***Full.*** Feasible for taxes set on fuels, technologies, other emissions, etc.
Subsidy	***Full.*** Feasible for subsidy set on energy fuels and technologies; energy service final devices, like gas-oven for coal-to-gas heating policy; and full electric vehicles purchasing behaviour.
Energy mix target	***Full.*** Energy mix targets for both full-economy sector and for specific sector, e.g. electricity generation, transportation, and industry (with sub-sectors).
Efficiency target	***Full.*** Efficiency target mainly for technologies, e.g. power generation efficiency; and fuel-economy standard upgrade for gasoline vehicles.
Regulations (thermal regulation in buildings, banning of diesel cars in urban areas, etc.)	***Full.*** Feasible for regulations for specific sector and energy commodity, e.g. limitation of vehicles with low emission standards in transportation sector, and regulations on low-carbon Ammonia production, etc.

Furthermore, the SDGs considered in the current version model include mainly health and affordable clean energy, with details shown in Table 4.11.

Table 4-11: Capability of the China-MAPLE assess other SDGs

SDG	Details
§3. Health (e.g., air-pollution related mortality)	In the local pollutant module, the local pollutant emissions are calculated and optimised. The local pollutant emission coefficient is directly linked to the energy processes/technologies, also considering any the end-of-pipe pollutant control measures. Damages to health can be evaluated based on measures of mortality (VSL – value of statistical life)
§7. Affordable and clean energy (e.g., traditional biomass use, %renewable energy)	Cost-effectiveness analysis for clean energy is included in the model framework, also considering the environmental co-benefits.

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4.6.10 Recent publications

Publication	Topic	Key findings
Yang et al. (2018a)	Air quality benefit of China's mitigation target to peak its emission by 2030	The model in this paper assesses the co-benefits of carbon mitigation in local pollutant reduction by linking carbon emissions to local air pollutants at the technological level.
Yang et al. (2018b)	Cost–benefit analysis of China's Intended Nationally Determined Contributions based on carbon marginal cost curves	Carbon tax is added into China-Multi-Pollutant Abatement Planning and Long-term Benefit Evaluation (China-MAPLE). Several conclusions are drawn from analysis based on MACC and China-MAPLE model.
Yang et al. (2018c)	The air quality co-benefit of coal control strategy in China	A bottom-up model of China-MAPLE is developed, to analyze the impact of coal control strategies on energy systems and local pollutant reductions.
Yang et al. (2016)	A scenario analysis of oil and gas consumption in China to 2030 considering the peak CO_2 emission constraint	A bottom-up energy system model is built and applied to analyse the fossil fuel consumption and carbon emissions in China up to 2030.
Yang et al. (2013a)	Incorporating environmental co-benefits into climate policies: A regional study of the cement industry in China	The model of this paper analyses the impacts of incorporating local air quality improvement and environmental co-benefits into the climate policy and mitigation technology assessment of the cement sector in China.
Yang et al. (2013b)	Quantifying co-benefit potentials in China's industry sector during its 12th five year	Co-benefits of mitigation measures in key industry sector are evaluated based on and the policy impact is further analysed based on marginal abatement cost during 12th Five Year Plan period.
Yang et al. (2018d)	Carbon Mitigation Pathway Evaluation and Environmental Benefit Analysis of Mitigation Technologies in China's Petrochemical Industry	This model evaluates the carbon mitigation effects and environmental co-benefits of mitigation technologies that have been long ignored in China's petrochemical and chemical industry.
Yang et al. (2018e)	Provincial-level Evaluation for the environmental health benefits of residential building energy conservation polices	The model of this article evaluates the effect of energy conservation policies and carbon mitigation efforts on reducing health damage in China's building sector.

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4.7 MUSE-Brazil

4.7.1 Overview

MUSE-Brazil is the implementation of the ModUlar energy system Simulation Environment (MUSE) framework for Brazil. Originally developed within the NERC-FAPESP funded project "Sustainable gas pathways for Brazil; from microcosm to macrocosm", as a collaborative effort between Imperial College and the University of São Paulo, MUSE-Brazil is a technology-rich agent-based energy system model for Brazil. It can be used to explore a variety of questions on how to promote a technology transition of the energy system in a five-region disaggregation of Brazil in a way that encompasses structural and behavioural constraints for the design of more realistic energy and climate change mitigation policies. Besides giving a new perspective on the energy system transitions, MUSE-Brazil enables flexible analysis of all sectors of the energy market as a whole or separately in a sector-by-sector fashion. It includes all sources of CO_2 emissions and shows the complex relationships within the energy system among technology, economics, and impact on the environment.

4.7.2 Key features of the model

4.7.2.1 Energy sectoral detail

MUSE-Brazil is a bottom-up technology-rich model of the whole energy system. It includes supply sectors, conversion (power and refinery) and demand sectors (residential, commercial, transport, industry, and agriculture). One of the main characteristics is its modular flexibility allowing representation of the specific drivers to technological investments and operation in each energy sector. The model is based on the MUSE modular framework, illustrated in Figure 4.8.

The MUSE-Brazil framework allows sector-specific modelling where the focus lies on an accurate description of the investment and operational decision making in each sector including a variety of methods reflecting the agent-based modelling approach. This is a distinct feature of MUSE-Brazil compared to other models, which either use a central planning approach to suggest optimal energy system changes or use a single investment metric across the economy. The focus on the investors' view within the modelling results in an arguably more realistic presentation of the energy market transition compared with the normative pathways from optimisation models. The energy equilibrium of MUSE is given by the market clearing algorithm (MCA) that connects all parts of the model and is responsible for the information flow between all sectors. The solution algorithm of MUSE is given by an inner loop for each time period and an outer loop for the simulation horizon (e.g., 2050 or 2100). The MCA iterates between sector modules until price and quantity of each energy commodity converge. The data exchange between the MCA and the sector modules is shown in Figure 4.9 for the specific case of the agriculture and land-use module, a technology-rich bottom-up model of agriculture and land-use.

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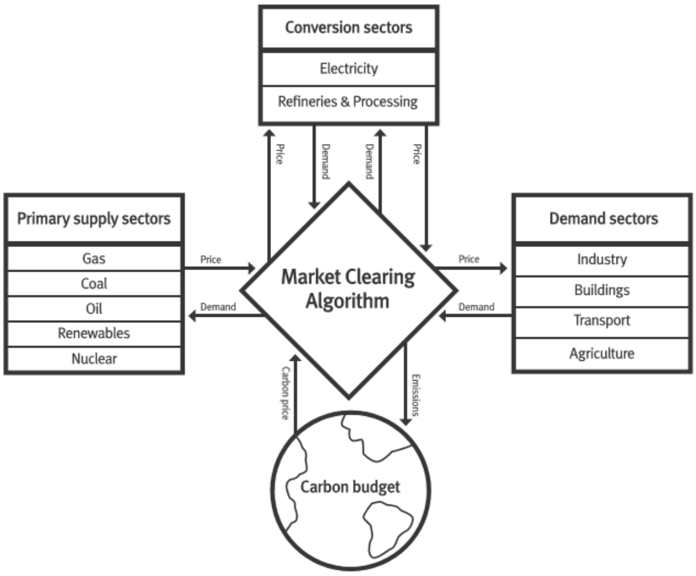

Figure 4-8: Representation of the MUSE-framework

Source: Garcia, I.K. et al. (2019a)

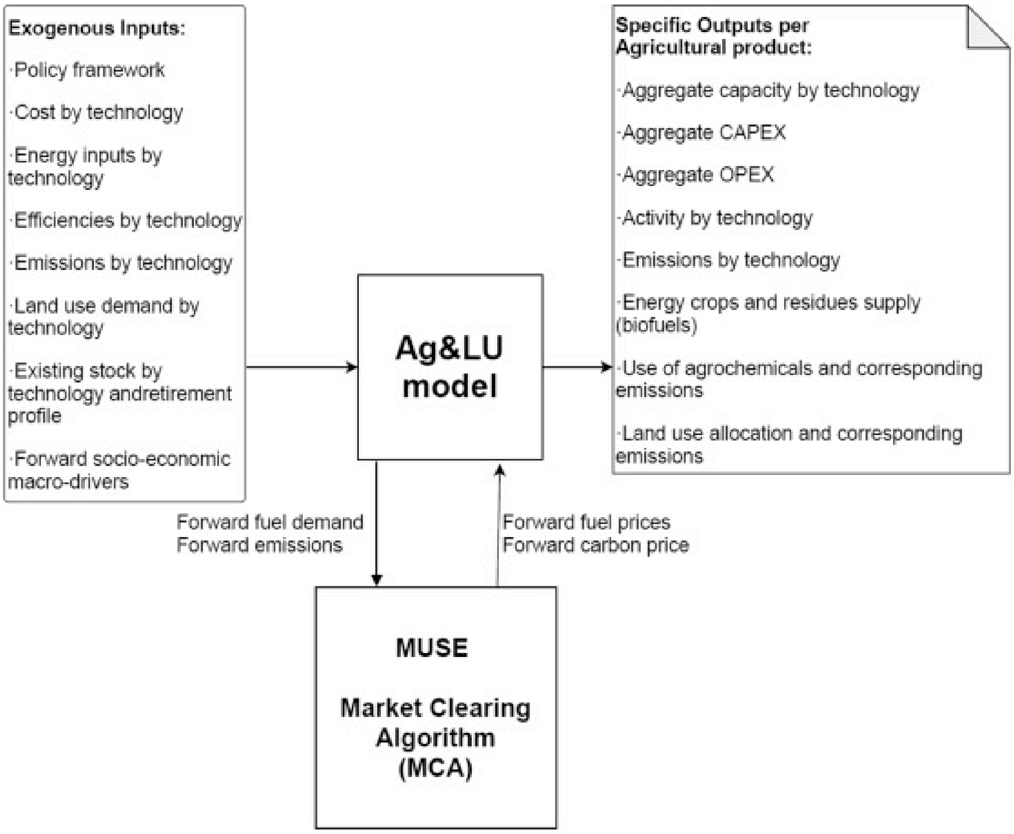

Figure 4-9: Ag&LU model integration into MUSE and data flow with the MCA

Source: Garcia, I.K. et al. (2019a)

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4.7.2.2 Geographic coverage

MUSE-Brazil uses a geographical disaggregation of Brazil based on 5 regions, shown in Figure 4.10, namely the North Region, the Northeast Region, the Central-West Region, the Southeast Region, and the South Region. In this way, the model aims to capture the high socioeconomic diversity that characterises the country.

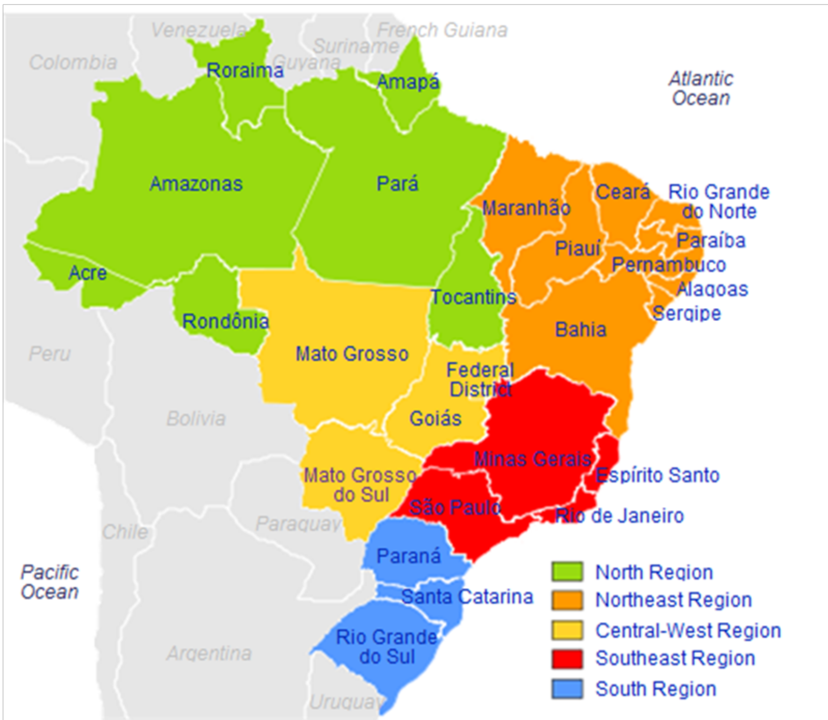

Figure 4-10: MUSE-Brazil regional disaggregation

4.7.2.3 Multi-year time periods

The time horizon over which MUSE-Brazil simulates the evolution of the energy system is divided into a user-chosen number of time-periods. In MUSE-Brazil, to be used in PARIS REINFORCE, 2015 is used as base year and 2020 represents the last calibrated year. The energy future is then simulated using milestone years defined with a 5-year interval to 2100. All years in each period are considered identical.

4.7.2.4 Intra-year time periods (time slices)

In addition to the multi-year time periods described above, in MUSE-Brazil 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 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 high availability of solar radiation). Specifically, the model uses three seasonal time-slices for industry, transport, agriculture, namely spring-autumn, winter, and summer. The model uses a set of thirty time-slices in power and buildings; these include six weekly diurnal slices and four week-end diurnal slices in each of three modelled seasons.

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4.7.3 Climate module & emissions granularity

The model tracks the three main sources of greenhouse gases - 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. MUSE-Brazil does not include a climate module that calculates the corresponding changes in the atmospheric concentration, the change in radiative forcing and the temperature change over pre-industrial times. Mitigation scenarios are rather modelled using a carbon budget approach set with the imposition of an emission limit for each milestone year.

4.7.4 Drivers of energy and other GHG-emitting service demands

The demand for services and goods drives the demand for energy in the model and results in greenhouse gas emissions (such as agricultural demand). More specifically, MUSE-Brazil considers energy service demand rather than demand for energy itself. Energy service demand is the service provided (e.g., heat, transport in passenger kilometres), rather than the kWh or PJ consumed in providing it (which is known as final energy consumption). In order to estimate energy service demand, data on specific consumptions by end-use technologies and their efficiencies is required.

Future demand projections of each service/goods in MUSE-Brazil are based on societal input variables, i.e. population and GDP. As a default assumption, MUSE-Brazil uses the shared socioeconomic pathway (SSP) representing the “middle-of-the-road” (SSP2) storyline and is obtained from the International Institute for Applied Systems Analysis (IIASA, 2018). It is expected that, during the PARIS REINFORCE project both GDP and population will be updated.

4.7.4.1 Economic growth

The country GDP is built on the SSP2 GDP estimates obtained from the IIASA database including recent updates and keeping a focus on the short-term trajectory. The GDP is then distributed across the five regions assuming a continuation of the historical year trends.

4.7.4.2 Population growth

The country population is built on the SSP2 population estimates obtained from the IIASA database including recent updates, especially in the short-term trajectory. The population is then distributed across the 5 regions assuming a continuation of the historical year trends.

4.7.4.3 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. Table 4.12 provides an overview of the services modelled in MUSE-Brazil. Among the modelled correlations, we use, for example:

$$Exponential\ (E):\ C = a * e^{b * GDPpc}$$

$$Log - \log\ (LL):\ lnC = a + b * \ln(GDP_{pc})$$

in which a and b are constants estimated in the regression and used as input to MUSE-Brazil. With reference to the agricultural sector, the historical trend of service demands are crop and meat demands between 1970 and 2015; these are regressed against the exogenously given macroeconomic drivers. As per capita income increases, population demand for agricultural products increase; however, the increase is under-proportional with income.

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In the case of food products, high income economies usually show to reach a per capita saturation level and, in some cases, even a decrease in demand for meat-based products, subsequently switching to vegetable-based diets.

Table 4-12: Services modelled in MUSE-Brazil in industry with material commodities (left) and services modelled in the remaining sectors, namely buildings, transport, agriculture (right)

MUSE material commodities	units	MUSE service commodities	units
Cement production	Mt	Space cooling	PJ
Ammonia	Mt	Space heating	PJ
Benzene	Mt	Water heating	PJ
Butadiene	Mt	Appliances	PJ
Ethylene	Mt	Lighting	PJ
Fertilizers	Mt	Cooking	PJ
Halogens	Mt	Private road	Million passenger-km
Methanol	Mt	Public road	Million passenger-km
Propylene	Mt	Freight road	Million tonne-km
Toluene	Mt	Freight rail	Million tonne-km
Xylene	Mt	Aviation	Million passenger-km
Iron	Mt	Navigation	Million tonne-km
Paper	Mt	Vegetable-based	PJ
Steel	Mt	Meat-based products	PJ
Aluminium	Mt	Forestry-based products	PJ
		Bioenergy products	PJ

4.7.4.4 Energy demand drivers and demand elasticities

Energy demands are driven by underlying drivers of socioeconomic growth, as well as energy price changes. While the estimate of the demand for goods and services is built from exogenous correlations on the GDP and population growth (as explained in the previous section), the demand for fuel changes depending on the competition/substitution among technologies, which then ultimately affects the fuel prices.

4.7.5 Calibration of the model

The calibration process determines what technologies exist in the energy system in the base year in each region of Brazil; the process of defining the technology stock aims to match fuel consumption and emissions sector by-sector as well as from land use. The base-year for calibration in MUSE is 2015, although 2020 would be considered in PARIS REINFORCE as the last updated year. To model the Brazilian energy system, data from the Energy Research Company (EPE, 2017) is the main source for calibration and validation, integrated with historical statistics from the International Energy Agency (IEA, 2020). For agriculture, forestry and land use, data from the Brazilian Geographic and Statistics Institute (IBGE, 2018) and FAO (2017) are used. Land demand for different Brazilian forest separated by biome as well as areas for silviculture are obtained from the Ministry of Environment (MME, 2018), while data for sugarcane crops from the Sugarcane Union Industry (UNICA, 2018).

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4.7.6 Mitigation/adaptation measures and technologies

MUSE-Brazil 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. The principal energy sector CO_2 mitigation technology options are as shown in Table 4.13.

Table 4-13 - Main CO2 energy system mitigation options in MUSE-Brazil

Upstream	
Synthetic fuel production	***Hydrogen production***
Coal to gas without CCS Biomass to gas without 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 and heat	
Electricity generation	***Variable renewables***
Coal with CCS Gas with CCS Nuclear Hydro (small and large) Biomass (with and without CCS) Geothermal Storage	Solar PV (ground and rooftop) Concentrated solar Wind (on and offshore) Tidal
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Hybrid / plugin hybrid electric vehicles (using biofuels mixture) Fully electric vehicles Fuel cell vehicles Hybrid / plugin hybrid hydrogen fuel cell vehicles Liquid hydrogen vehicles Flexible vehicles (using biofuel mixtures)	Electric Hydrogen
Air	***Marine***
Biofuels in fuel mix Hybrid electric planes Hybrid electric planes using biofuels	Gas / LNG Hydrogen Biofuels
Buildings (commercial/residential)	
Heating	***Lighting***
Gas replacing coal / oil Gas / biomass / electricity / hydrogen boilers (integrated with solar thermal) Gas / biomass co-generation (CHP and micro-CHP) District heating (gas / biomass / waste heat), standalone or integrated with solar thermal or heat pumps Efficiency Biomass / electricity / hydrogen cooking	LEDs Efficiency
Appliances	***Cooling***
Efficiency	Efficiency Heat pumps Heat pumps integrated with solar thermal
Industry	
Iron and steel / pulp and paper / chemicals / aluminium / cement	***CCS***
Gas replacing coal / oil Biomass Biomethane Electrolysis (for ammonia production) Efficiency	CCS in iron & steel (w/out bioenergy) CCS in cement (w/out bioenergy) CCS in chemicals (w/out bioenergy) CCS in pulp and paper (w/out bioenergy) CCS in aluminium (w/out bioenergy)
Agriculture	
Energy	***Non-CO2***
Gas replacing fuel oil Biomass Electricity Mechanisation	Mechanisation

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4.7.7 Economic rationale and model solution

The rationale of the model and the solution approach in MUSE-Brazil, is the same used in MUSE-Global (see D7.1) and descends from the agent-based simulation approach proper of the MUSE modelling environment.

MUSE-Brazil simulates a microeconomic equilibrium on the energy system. It consists of modular independent agent-based sector modules, joined by a market clearing algorithm, as shown in Figure 4.8.

The market clearing algorithm iterates across all sector modules, interchanging price and quantity of each energy commodity in each region, until an equilibrium of the exchanged prices/quantity 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 CO_2 emissions price is then set in the MCA 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).

MUSE-Brazil 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 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.

MUSE-Brazil is a limited-foresight model that strives to represent the frictions and challenges that could occur as the world aim for systemic technology change to achieve climate change mitigation over the coming decades.

4.7.8 Key parameters

MUSE-Brazil takes a technology-rich bottom-up approach, where specific engineering technologies are characterised alongside their input/output commodities. These technologies, also called “processes”, convert commodities from one form to another - e.g., a chiller that converts electricity to cooling or a CHP plant that converts gas to electricity and heat. Therefore, data regarding cost, efficiency, lifetime, availability, etc. are required for each process to characterise possible future energy system.

Among the most important parameters to monitor, discuss and evaluate in the framework of the PARIS REINFORCE project for a successful integration of this model with the other tools and analyses:

- Biomass potential for energy purposes (forest and agriculture residues, organic wastes, etc.)
- Forestry conservation and land use emissions
- Renewable potentials and annual variability of intermittent resources
- Cost evolution for the most promising technologies in each sector (renewable electricity, electric vehicles, etc.)
- Cost evolution for emerging technologies (second generation biofuels, new industrial processes, etc.)
- Deployment of low-carbon technologies, such as carbon capture and storage, afforestation, renewables, electric vehicles
- Energy conservation potentials in buildings
- Impact of policies

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

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experiences, and the discussion with the partners (modellers).

4.7.9 Policy questions and SDGs

4.7.9.1 Key policies that can be addressed

MUSE-Brazil is usually applied by specifying either a carbon tax or a carbon emission limit to the whole country or selected regions. This acts as a proxy for all other climate-related policy. However, a further range of policy levers are possible:

- Capacity factors limits on fossil fuel power generation plants (e.g., to simulate minimum or maximum desired levels of operation)
- Subsidies on selected technologies (through adjusting their costs)
- Constraints on the availability of selected 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), 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).

As policy analyses are undertaken, they can be modelled within the overarching agent-based framework, allowing a more realistic representation of the constraints to the energy system transition.

4.7.9.2 Implication for other SDGs

MUSE-Brazil does not calculate non-climate SDGs directly. However, it is possible to perform "off-model" calculations to estimate many of the SDG implications. For example, the model 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, the presence of an agriculture module integrated with land-use, allow to provide outputs that could inform SDG15, related to "Life on Land".

4.7.10 Recent publications using the MUSE-Brazil model

Study	Focus	Key findings
Kerdan, I.G. (2019) a	This paper proposes an analysis with MUSE 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 $GtCO_2$ by 2050 through reforestation. In this scenario, the capital investment in carbon sequestration and storage would be substantially reduced.
Kerdan, I.G. (2019) b	This analysis use MUSE integrated with a gas infrastructure model to assess gas infrastructure	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

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	pathways for the southern states of Brazil	pre-salt production, LNG imports and imports from a new Argentinian pipeline.
Kerdan, I.G. (2019) c	This paper uses MUSE to explore the complex relationship between sugarcane production, deforestation and fossil fuel resource exploitation under two 2°C scenarios for Brazil obtained 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 existing gas infrastructure capacity.
Kerdan, I.G. (2019) d	This paper proposes 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.

4.7.11 References

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4.8 The North American TIMES Energy Model (NATEM)

4.8.1 Overview

The North American TIMES Energy Model (NATEM) is an optimisation model that belongs to the TIMES family of models—for a brief explanation of TIMES see the MAPLE model description in Section 4.6.1. NATEM is currently the only detailed optimisation model in North America. The 23-region model optimises the entire integrated energy systems, as well as non-energy GHG emitting sectors, of Canada, the United States and Mexico. By capturing the large diversity of energy systems and policies across the three countries using a consistent modelling approach, it provides a rational framework for supporting adequate decision-making related to climate policies over the 2050 horizon. Model results have been used by decision makers from public and private organisations to draft the Climate Action Plan, identify research priorities for reducing mitigation costs, prepare energy transition outlooks, assess the impacts of energy projects and evaluate circular economy strategies.

4.8.2 Key features of the model

4.8.2.1 Energy sectoral detail

NATEM offers a comprehensive representation of the energy system of each of the North American jurisdictions (Figure 4.11). It also models inter-jurisdictional and international flows of energy and material commodities. The model is driven by a set of about 70 end-use demands for energy services in five sectors: agriculture, commercial, industrial, residential and transportation.

For the energy supply side, NATEM captures all sectors including electricity and heat generation in many details. Other supply sectors include fossil fuels extraction, upgrading and transport, uranium extraction and transport, petroleum refining, bioenergy production, natural gas liquefaction and exports, hydrogen supply chain, etc. Primary energy resources include conventional and unconventional fossil fuels reserves (oil, gas, and coal), renewables potentials (hydro, geothermal, wind, solar, tidal and wave), uranium reserves and biomass (various solid, liquid and gaseous sources). Carbon capture options are available in the electricity and industrial sectors. Sequestration potentials exist for enhanced oil recovery, in oil and gas fields (onshore and offshore) and in deep saline aquifers.

In each sector, a repository includes a large number of new technologies that are in competition to satisfy each end-use demand including existing technologies, improved versions of existing technologies and new technologies.

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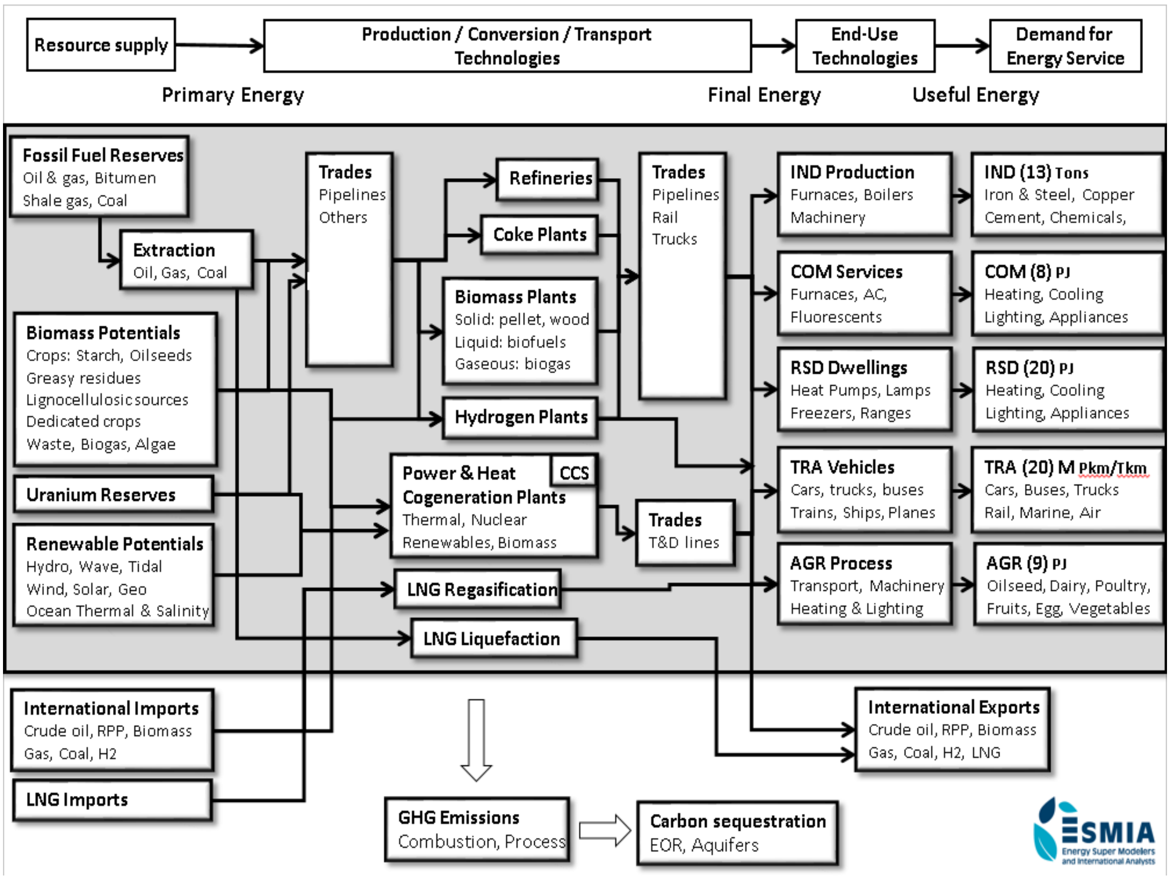

Figure 4-11: Representation of the NATEM energy system for each region

Source: Vaillancourt et al. (2018c)

4.8.2.2 Geographic coverage

NATEM covers Canada through thirteen regions (each of the thirteen provinces and territories), the United States through nine regions (the official census regions) and Mexico through one region (Figure 4.13).

4.8.2.3 Multi-year time periods

The time horizon over which NATEM simulates the evolution of the energy system is divided into a user-chosen number of time-periods. The model is currently solved for the 2011-2050 timeframe through ten time periods of variable lengths. Short time periods (1 to 2 years) are defined at the beginning of the horizon, while longer time periods (5 years) are considered afterward, as uncertainties related to data are increasing over time. Current milestone years (for which results are generated) are: 2011, 2013, 2015, 2020, 2025, 2030, 2035, 2040, 2045, and 2050. All years in a given period are considered identical. For all quantities such as installed technology levels, power plant capacities and energy and emissions 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 of the years in that period.

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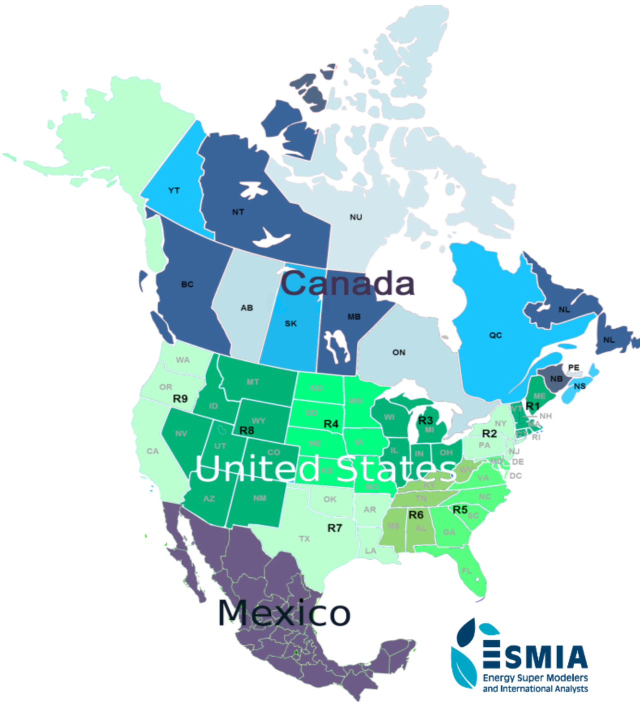

Figure 4-12: Regional representation in NATEM

Source: ESMIA Consultants (2019). Website: Model Description. Retrieved from www.esmia.ca

4.8.2.4 Intra-year time periods (time slices)

In addition to the multi-year time periods described above, in NATEM there are time divisions ***within*** a year, called "time slices", which may be defined by the user, so as to capture different weather, consumer behaviours, and energy demand conditions at different times of the year. There are currently sixteen time slices representing four seasons a year (spring, summer, fall and winter) and four intraday periods (day, night, morning peak, evening peak). The MAPLE model documentation (Section 4.6.2.4) provides further detail of the purpose of time-slices in the TIMES framework.

4.8.3 Climate module & emissions granularity

The model tracks all GHGs, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) from all sectors of the national inventories, except land use, land-use change and forestry (LULUCF). NATEM does not include a climate module that calculates the corresponding changes in the atmospheric concentration, the change in radiative forcing and the temperature change over pre-industrial times.

4.8.4 Drivers of energy and other GHG-emitting service demands

The NATEM model requires inputs concerning the degree to which energy service demands, as well as demand for other goods and services which result in GHG emissions, will grow over the course of next decades in the different countries. It does this by using various socioeconomic inputs, as described below. Data will be revised and updated before running the model under the PARIS REINFORCE project.

Demands for energy services are currently projected through 2050 using a coherent set of socioeconomic assumptions from the projections of the National Energy Board (NEB, 2017) for Canada, from the Annual Energy Outlook (EIA, 2018) for the United States, and various national sources for Mexico (CONAPO, 2012; SENER, 2014;

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PRODESEN, 2018). Demands for energy services are projected using national sources specific to the three countries and not a single source. Demands are ultimately projected through 2050 from the 2011 base year using the following growth index (Table 4.14):

Table 4-14: Key socio economic inputs in NATEM

GDP	**Index in 2050 (2011=1)**
Canada	1.93
United States	2.16
Mexico	3.70
Population	**Index in 2050 (2011=1)**
Canada	1.33
United States	1.24
Mexico	1.29

It is important to note that macroeconomic drivers, such as Gross Domestic product (GDP) and population, are not the only factors used to project end-use demands for energy services. These projections formed the basis for projecting end-use requirements in the different sectors, but many other factors are considered: future announced projects, degree-day projections, number of households, commercial surface, industrial gross output, etc.

4.8.4.1 Economic growth

GDP projections are based on national specific information. Growth rates vary significantly across the three countries, where the GDP is expected to double by 2050 in Canada and the United States, while a more than three-fold increase is projected for Mexico. Although the economic structure varies from a country to another, the three economies rest on abundant energy resources, both fossil and renewables.

4.8.4.2 Population growth

Population projections are also based on national specific information. Growth rates are similar across the three countries with Canada having the highest rate. This estimation takes into account historical trends, adjusted with immigration, emigration and interprovincial migration and track on the National Energy Board's population by province as published by the National Energy Board (NEB 2017; TEPF, 2016).

4.8.4.3 Sectoral growth

The growth in the industrial, agricultural and commercial sectors in each region is partially derived from the national's overall GDP growth, with each sector's share of total GDP changing over time, and from the expected/planned production levels, constructions, and development of certain activities. 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.

4.8.4.4 Energy demand drivers and demand elasticities

As with MAPLE, described in Section 4.6.4.2, energy demands are driven by underlying drivers of socioeconomic growth, as well as energy price changes.

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4.8.5 Calibration of the model

The NATEM model is calibrated to the 2011 base year using mainly country-specific information (e.g. EIA, 2018; PRODESEN, 2018; Statistics Canada, 2015), with the projections for the key energy flows, energy-related investments and stocks (e.g. installed technology capacity) further calibrated as new datasets become available.

NATEM is constantly updated; the version to be used in PARIS REINFORCE will have an updated energy statistics calibration (the most useful combination among the key international and local sources) to the most recent years. The main variables to be calibrated are: the capacities/stocks and operating levels of all technologies, the extracted, exported, imported, produced, and consumed quantities for all energy carriers, and the representation of new policy- and target-related elements.

In order to better isolate the effects of a new policy and/or have a clear picture of the remaining efforts necessary to achieve mitigation goals, reference scenarios include government policies already in place such as existing action plans on climate change, transport electrification targets, renewable penetration targets, Corporate Average Fuel Economy (CAFE) standards, building codes, regulations on the minimum content of renewables in conventional fuels, carbon taxes, as well as the existing carbon market between Quebec and California.

4.8.6 Mitigation/adaptation measures and technologies

TIMES models enable capturing in particular substitutions of energy forms (e.g., switching to low-carbon fuels) and energy technologies (e.g., use of battery-electric vehicles instead of vehicles equipped with an internal combustion engine running on conventional fuels) to comply with climate policy targets.

NATEM is such 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 capturing 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 NATEM model simulates mitigation. The principal mitigation technology options are as shown in Table 4.15. Options marked with an asterisk (*) are currently not in the database but could be included during the project period in harmonisation with the other modelling teams. Data will be revised and updated in the framework of the *Paris Reinforce* project, and in accordance with the international database and feedback of local experts.

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Table 4-15: Main GHG energy system mitigation options in NATEM

Upstream and downstream	
Synthetic fuel production	**Hydrogen production**
Coal to gas without CCS* Coal to liquids without CCS* Biomass to gas without CCS 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*
Oil & gas extraction and refining	**Other**
Electricity Nuclear (small units)	
Electricity and heat	
Electricity generation	**Heat generation**
Coal with CCS Gas with CCS Nuclear (fission and fusion) Hydro (dam and run-of-river) Biomass (with and without CCS) Geothermal Solar PV Solar CSP Wind (onshore and offshore) Tidal Marine	Coal with CCS Gas with CCS Oil with CCS 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 Efficiency	Electric Hydrogen Efficiency
Air	**Marine**
Biofuels in fuel mix Hydrogen planes* Efficiency	Gas Hydrogen Biofuels Efficiency
Buildings	
Heating	**Lighting**
Gas replacing coal / oil Biofuels Electricity Hydrogen Efficiency	Efficiency
Appliances	**Cooling**
Electricity Efficiency	Electricity Efficiency

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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 (technology replacement)**
CCS in iron and steel CCS in cement CCS in chemicals	Advanced technologies for aluminium (inert anodes) Cement clicker replacement
Agriculture	
Energy	**Non-Energy**
Biomass Electricity	Additives to reduce enteric fermentation Manure & Digester
Waste	
Solid waste	**Wastewater**
Energy recovery for organic material Landfill gas capture + renewable gas or electricity	
Fugitive emissions	
Flare gas recovery	

4.8.7 Economic rationale and model solution

The TIMES modelling framework rationale, as a least-cost optimisation model, is detailed in the MAPLE documentation, in Section 4.6.7.

4.8.8 Key parameters

NATEM relies on a technology-rich database that has been developed and continuously updated for the past 10 years, through partnerships and accesses to other energy optimisation model databases used worldwide, research projects in several universities with important Canadian research funding, consulting projects for public and private organisations in North America, constant technology watch and literature review, and collaboration with world class energy modellers to develop rigorous assumptions and robust approaches through ETSAP-IEA. With thousands of specific (existing and future) technologies, characterised with their techno-economic attributes, and hundreds of commodities, many datasets can be extracted and reported.

Given the very rich and diversified energy systems in North America, the following key information are considered as the most important parameters to monitor, discuss and evaluate in the framework of the PARIS REINFORCE project for a successful integration of this model with the other tools and analyses:

- Conventional and unconventional oil and gas reserves (located, enhanced recovery, new discoveries);
- International markets for oil and gas exports (quantities and/or prices);
- Biomass potential for energy purposes (forest and agriculture residues, organic wastes, etc.);
- Renewable potentials and annual variability of intermittent resources;
- Sequestration potentials in oil and gas field as well as saline aquifers;
- Information about new projects, namely hydro dams and interconnections that are currently under construction or already scheduled for future construction, as well as pipeline projects;
- Cost evolution for the most promising technologies (renewable electricity, electric vehicles, etc.);
- Cost evolution for emerging technologies (second generation biofuels, new industrial processes, etc.);
- Energy conservation potentials in buildings (roof insulation, duct sealing, etc.);

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- Existing policies, targets, plans; etc.

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

4.8.9 Policy questions and SDGs

4.8.9.1 Key policies that can be addressed

As for all the TIMES-based models, the NATEM predominantly works by specifying either a GHG price (e.g. a carbon tax) or a GHG limit (e.g. an upper bound constraint) in one or several regions, or alternatively for all regions simultaneously. Additionally, the following further policies and measures can be implemented: subsidies or taxes on specific technologies, renewable portfolio standards, minimum renewable content in conventional fuels, phase-out programs and moratoria on some energy type (e.g. nuclear or hydrocarbon), investment growth rate projections, etc.

This allows NATEM to perform a number of energy and climate policy-relevant investigations. Indeed, NATEM has been used to assess the implications of meeting ambitious GHG mitigation goals on the energy system configuration and cost, under many different economic and technical assumptions. Model results have been used by decision makers at national, regional and city levels in North America to i) **draft Climate Action Plan** and **define optimal sequences for the introduction of mitigation measures** and ii) **identify strategic research priorities for reducing mitigation costs** while contributing to the development of a sustainable economy. For example:

- *Quebec Ministry of Environment and Climate Change* and *Quebec Ministry of Finance* in preparation of the *Climate Action Plan*: the model was used to identify optimal GHG reduction trajectories for achieving the official targets taking into account uncertainties related to the evolution of demands, social acceptability, and technological innovation (Dunsky et al., 2019).
- *Environmental Commissioner of Ontario* in preparation of its *Climate Action Plan*: the model was used to compare costs and other impacts for i) achieving Canadian only mitigation targets and ii) achieving both Ontario and Canadian mitigation targets (Vaillancourt et al., 2018d).
- *Metropolitan Montreal Community (MMC)* in preparation of its *Climate Action Plan*: the model is used in support to the development of an action plan and define priorities in consultation with key stakeholders to achieve carbon neutrality in 2050 (ongoing project).

NATEM was also used in a variety of other applications to support decision-makers in governments, industries and associations:

- With the **preparation of Canadian energy outlooks,** such as the most recent *Canadian Energy Outlook* (Langlois-Bertrand et al., 2018) with an ambitious scenario including a GHG reduction target of 80% by 2050 compared to 1990 (the first of its kind in over a decade covering Canada and its 13 jurisdictions) and the *Trottier Energy Futures Project* (TEFP, 2016) which is now a reference in Canadian universities and government offices to understand how Canada can achieve its official targets.
- With the **preparation of technology roadmaps:** the model was used to support a *gas company* in preparation of its long-term *Strategic Plan 2015-2030* to analyse the penetration rates of renewable natural gas under mitigation scenarios (confidential project).
- With **technological penetration rate estimations:** the model was used to support the *Biofuel Canada Network* to derive market penetration rates of emerging biofuels to 2050 under GHG mitigation scenarios (Levasseur et al., 2016).
- With **economic and environmental impact assessments of future energy projects**: the model was

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used to support the *Prime Minister Office* and *Quebec Ministry of Environment and Climate Change* in developing their position on the exploitation of hydrocarbon on the Anticosti Island in a GHG mitigation context (Vaillancourt et al., 2018c).

- With **energy security issues**: the model was used to evaluate the impacts of the TransCanada Energy East pipeline on the oil supply-demand dynamic and prices in Eastern provinces, Newfoundland and Labrador especially for the *Centre for Applied Research in Economics (CARE)* (Vaillancourt et al., 2015).
- With the **evaluation of circular economy strategies**: the model was used to support the *Quebec Ministry of Energy and Natural Resources* to assess the techno-economic potential of circular economy strategies for the iron, copper and lithium mining industries (Vaillancourt et al., 2018e).

4.8.9.2 Implications for other SDGs

NATEM does not automatically calculate the implications for non-climate SDGs of its least-cost energy system to meet prescribed climate targets. However, it is possible to take its outputs and perform "off-model" calculations to estimate many of the SDG implications or to use them as input in other models or tools. A number of other SDGs can be taken into consideration and investigated indirectly making use of the NATEM model (Table 4.16).

Table 4-16: Capability of the NATEM model to assess other SDGs

SDG	Details
§1. Poverty	Impacts on energy prices in different sectors can be used and trade-offs between energy poverty reduction measures versus energy consumptions can be partially explored.
§3. Health	Life-cycle analysis can be used to assess other environmental impacts than GHGs of model solutions. Other pollutants can be tracked and impacts on air quality and health assessed with a spatial distribution model.
§7. Affordable and clean energy	Cost-effectiveness of energy technologies and commodities within a specific storyline.
§8. Decent work & growth	Energy export revenues can be tracked and analysed to evaluate the corresponding impacts on the global budget. Model outputs (energy prices, etc.) can be used as input in a general equilibrium model to estimate impacts on GDP and jobs.
§9. Industry, Innovation, Infrastructure	Model can be used to assess the techno-economic potential of emerging technologies in industries.
§11. Sustainable cities/communities	When model development allows it (enough spatial disaggregation), GHG mitigation studies can be performed at the city level.
§12. Responsible Cons.-Production	When model development allows it (enough sectoral details with modelling of material commodities), circular economy strategies can be assessed.
§15: Life on land	Afforestation measures can be taken into account through exogenous supply curves. Land-specific constraints (natural and regulatory) can be introduced.

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4.8.10 Recent publications

Study	Focus	Key findings
Vaillancourt et al. (2018a)	The role of bioenergy in low-carbon energy transition scenarios: A case study for Quebec (Canada).	Our study envisions a much larger penetration of bioenergy (up to a threefold increase) than the one proposed by the government of Quebec in its 2030 Energy Policy to achieve the GHG mitigation target.
Vaillancourt et al. (2018b)	The Canadian contribution to limiting global warming below 2ºC: An analysis of technological options and regional cooperation.	The main transformations include significant energy efficiency improvements, greater penetration of electricity and bioenergy in all end-use sectors in 2050, a rapid decarbonisation of electricity production and a shift away from fossil fuels. Canada would benefit from achieving greater cooperation between jurisdictions because of the large diversity of energy systems.
Vaillancourt et al. (2018c)	The role of new fossil fuels projects in a decarbonising energy system: A case study for Quebec.	Results indicate the 2050 GHG emission levels would increase by nearly 7% in the reference case. Greater total GHG reductions would thus be required from the baseline at a significantly higher marginal cost.
Astudillo et al. (2017)	Can the household sector reduce global warming mitigation costs? Sensitivity to key parameters in a TIMES techno-economic energy model.	Results indicate that peak demand would rise by 30% due to global mitigation efforts, but it can be effectively reduced by interventions in the residential sector. Heat pumps are the most cost-effective heating technology, despite their lower efficiencies in cold climates. Better-insulated building envelopes have an important uptake in new houses, reducing by 14% the mitigation costs.
Levasseur et al. (2016)	Assessing butanol from integrated forest biorefinery: A combined techno-economic and life cycle approach.	Results show that (i) the energy efficiency of the butanol production process is a critical aspect to make butanol a competitive fuel; (ii) with a 50% internal heat recovery, butanol has a role to play for transport under climate policy scenarios; and (iii) higher supply costs for feedstock might undermine the competitiveness of butanol in the medium term (2030), but probably not in the long-term (2050).
Vaillancourt et al. (2017)	Exploring deep decarbonisation pathways to 2050 for Canada using an optimisation energy model framework.	Results show that three fundamental transformations need to occur to achieve GHG reduction targets: electricity should represent up to 57% of final energy by 2050, electricity generating supply should achieve nearly complete decarbonisation by 2025 and final energy should decrease by 20% relative to the baseline by 2050.

4.8.11 References

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4.9 The TIMES- Central Asian Caspian Model (TIMES-CAC)

4.9.1 Overview

As with MAPLE and NATEM, TIMES-CAC uses the TIMES modelling framework, as described in Section 4.6.1. The integrated bottom-up partial-equilibrium energy system model of the Central Asian Caspian (CAC) Area, titled TIMES-CAC, assembles the four separate but structurally-consistent single-region TIMES country models of Azerbaijan, Kazakhstan, Turkmenistan, and Uzbekistan[2] by interconnecting them through the representation of energy flows and emission permits exchanges. The multiregional model is thought and designed as a comprehensive framework, able to explore national and/or supra-national forces, in a long-time horizon (until 2050), with the aim to test the effects of long-term energy export strategies on the energy system of the CAC countries and analyse trade-off curves between “risk” indicators and key KPIs, such as the system cost, the quantities exported and the corresponding revenues, as well as the emission reduction ambitions.

4.9.2 Key features of the TIMES-CAC model

4.9.2.1 Energy sectoral detail

The key components of the TIMES-CAC model are the technologies for the production of primary and secondary commodities (mining and extractions processes, power plants, refineries, etc.) together with the most representative appliances and devices of the demand sectors (boilers, light bulbs, road vehicles, etc.). The energy system development of each model region is driven by a set of demands for energy services in all sectors: agriculture, residential, commercial, industry, and transportation.

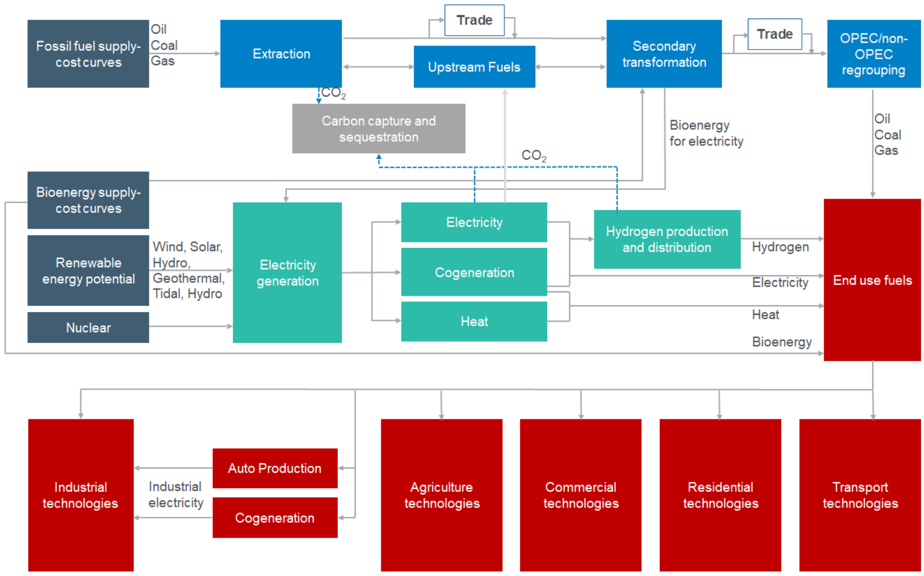

Figure 4-13: Representation of the TIMES-CAC energy system for each country

Source: Authors, based on the original design of Loulou and Labriet (2007)

[2] Two extra “implicit” regions, Kyrgyzstan and Tajikistan, can be enabled to further explore electricity synergies and emission reduction cooperative strategies. In its default version, the model is built upon four regions only and it is named TIMES-CAC-4R.

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4.9.2.2 Geographic coverage

In its default version, the TIMES-CAC model covers four explicit regions (countries). A number of export routes (towards three key areas of energy transit/consumption, namely Russia, Europe and China, which are all well-represented in the PARIS REINFORCE consortium) are also simulated, as shown in the following figures (structure and data as included in the current version of the model).

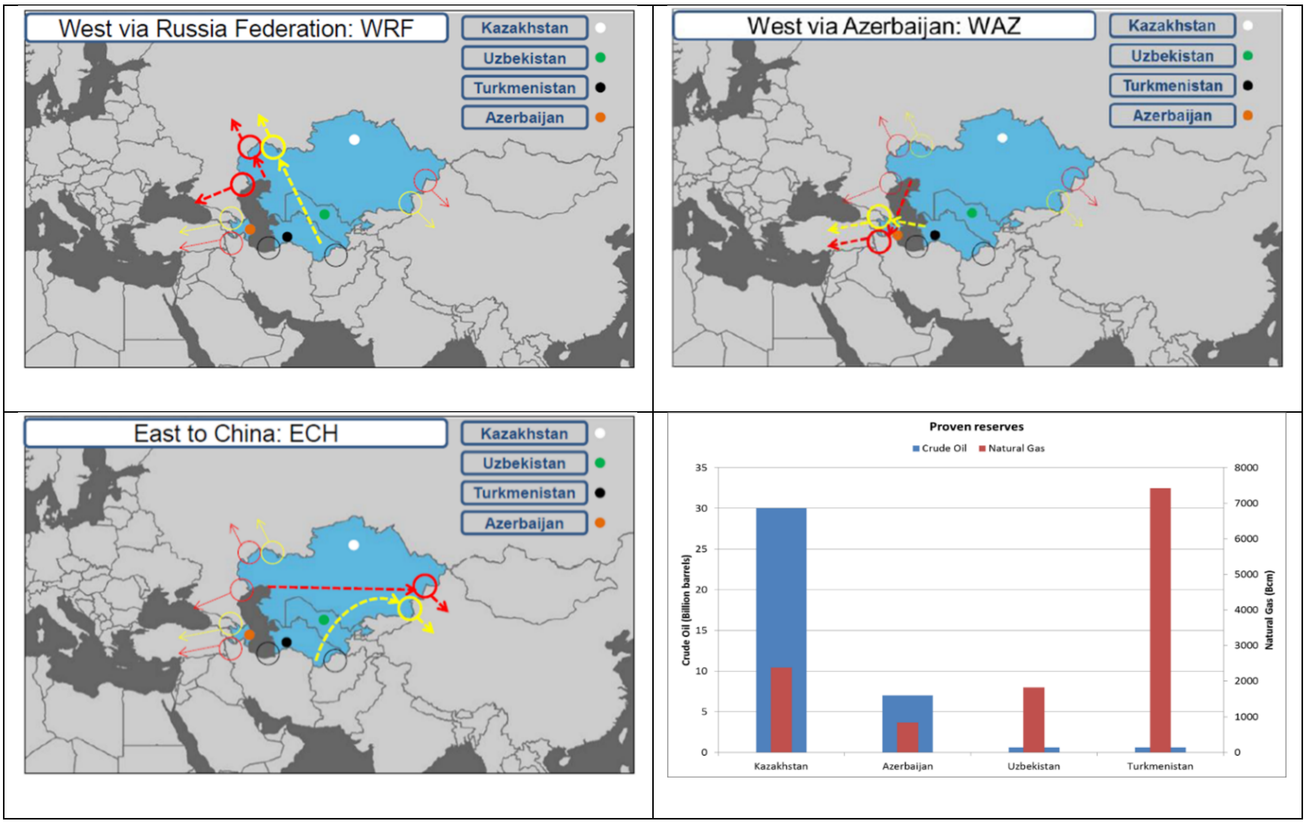

Figure 4-14: Regional representation in TIMES-CAC, connection with the rest of the world (RoW)

Source: Authors, elaborations for internal reports and conferences. Oil trade routes (red arrows) and gas trades routes (yellow arrows). A Southern route "to India" (through Afghanistan) can also be analysed.

4.9.2.3 Multi-year time periods

The time horizon over which TIMES-CAC simulates the evolution of the energy system is divided into a user-chosen number of time periods. In its default (current) version, the model runs from 2011 (base year) to the medium-to-long term through six periods (the representative years of which are: 2011, 2013, 2020, 2030, 2040, and 2050). All years in a given period are considered identical. For all quantities, such as installed technology levels, power plant capacities and energy and emissions 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 of the years in that period.

In the framework of the project, the model can be further calibrated to different references years and run different horizons/organisation of periods, if necessary.

4.9.2.4 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, consumer behaviours, and

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energy demand conditions at different times of the year (see Section 4.6.2.4 for the MAPLE model for further details on time-slices in the TIMES modelling framework). There are currently nine time-slices representing summer daytime, summer night time, and a peak moment in summer, winter daytime, winter night time, and a peak moment in winter, and an intermediate season day time and night time and peak moment in the intermediate season.

4.9.3 Climate module & emissions granularity

The model tracks the three main sources of GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20). A special module of the TIMES-CAC model can be enabled to let two more countries of the Central-Asian region (virtually modelled), to participate in the GHG emission reduction effort (through a virtual market trading scheme extended to four-plus-two regions of the area).

4.9.4 Drivers of energy and other GHG-emitting service demands

The TIMES-CAC model requires inputs concerning the degree to which energy service demands, as well as demand for other goods and services which result in GHG emissions (such as agricultural demand), will grow over the course of next decades in the different countries. It does this by using various socioeconomic inputs, as described in the following table (current default values) and sections. Data will be revised and updated before running the model under the PARIS REINFORCE project.

Table 4-17: Key socioeconomic inputs in TIMES-CAC

	Indicator	Values	In 2009	Growth index (2009=100)			
				2020	2025	2030	2050
AZJ	Population	Million	8.8	118	124	130	*1.5 wrt the BY
	GDP per capita (&)	US$'2000ppp	8702	175	217	251	Study-specific
	Aggregate demand for energy services	Index (+)	100	199	265	328	Study-specific
KZK	Population	Million	15.9	118	124	130	*1.5 wrt the BY
	GDP per capita (&)	US$'2000ppp	8400	161	196	238	Study-specific
	Aggregate demand for energy services	Index (+)	100	167	209	264	Study-specific
TKM	Population	Million	5.1	118	124	130	*1.5 wrt the BY
	GDP per capita (&)	US$'2000ppp	9859	175	217	251	Study-specific
	Aggregate demand for energy services	Index (+)	100	179	226	269	Study-specific
UZB	Population	Million	27.8	118	124	130	*1.5 wrt the BY
	GDP per capita (&)	US$'2000ppp	2395	175	217	251	Study-specific
	Aggregate demand for energy services	Index (+)	100	185	238	283	Study-specific
CAC-4R	Population	Million	57.6	118	124	130	*1.5 wrt the BY
	GDP per capita (&)	US$'2000ppp	5678	170	208	246	Study-specific
	Aggregate demand for energy services	Index (+)	100	178	226	278	Study-specific

4.9.4.1 Economic growth

As is the case for almost all the most important energy-producing countries, the CAC countries are also highly dependent on energy exports, and this dependence results in a very large share of the energy sector to the GDP and fundamental (critical) contributions to the State budgets. Economic growths are based on national specific projections for the medium-term, and on hypotheses (study- and scenario-specific) for the longer horizon. In

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general terms, the analysed storylines always assume a (quite fast) growth in domestic GDPs for all the cases and countries, that in a baseline case is equivalent to an economic trend of around +4.5% (in terms of GDP, in average, to 2050).

But due to the abovementioned characteristics, economic growths in the CAC area (by country) should be always properly assessed and considered within a self-consistent (energy-related) storyline, in order to keep a certain degree of robustness of the scenario and of the projections.

4.9.4.2 Population growth

Population growths are also based on national (local) specific information in the medium term and on assumptions in the longer horizon (mainly inherited by a specific analysis for Kazakhstan), that result in a population growth rate of +1.2%, in average, in the long-term (2050), for the multiregional area. It is worth noting that, according to some local experts, the international analyses often "underestimate" the population growth rates of the area, due to the incorrect comparison with Russia (and the Former Soviet Union) and with the Russian ethnic groups (lower birth rates).

It should also be noted that the TIMES-CAC model can be adjusted to use other socioeconomic growth projections aside from the default.

4.9.4.3 Sectoral growth

The growth in the industrial, agricultural and retail business sectors in each region is partially derived from the national's overall GDP growth, with each sector's share of total GDP changing over time, and from the expected/planned production levels, constructions (e.g. square meters for services), and development of certain activities. 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.

4.9.4.4 Energy demand drivers and demand elasticities

The economic, population and sectoral growths (e.g. physical production of industrial activities) are used as specific drivers for the growth in energy demands, in the same way as for the MAPLE and NATEM models, as detailed for the MAPLE model in Section 4.6.9.2.

4.9.5 Calibration of the model

The TIMES-CAC model is calibrated for the initial period (currently 2011) using a combination of IEA world energy statistics for the year 2011 and country-specific information, with the projections for the key energy-related investments and stocks (e.g. installed technology capacity) further calibrated until 2013-2015. The current intention is that the version of TIMES-CAC to be used in PARIS REINFORCE will have an updated energy statistics calibration (the most useful combination among the key international and local sources) to the most recent years. The main variables to be calibrated include: the capacities/stocks and operating levels of all technologies; the extracted, exported, imported, produced, and consumed quantities for all energy carriers; and the introduction/representation of recent (new) policy- and target-related elements (if any).

4.9.6 Mitigation/adaptation measures and technologies

TIMES-CAC is a technology-rich model that represents most major fossil fuel and low-carbon technologies that are envisaged to be available (for those systems) for at least the first half of the 21st century. By simulating the

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substitution of low-carbon for high-carbon technologies in response to their relative costs, as well as emissions constraints and/or carbon prices, the model simulates mitigation. The principal energy sector CO_2 (and non- CO_2) mitigation options are shown in the following table (the options that are not currently available but can be added in the model are marked with an asterisk*). Data will be revised and updated in the framework of the PARIS REINFORCE project, and in accordance with the international database and feedback of local experts.

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Table 4-18: Main GHG energy system mitigation options in TIMES-CAC

Upstream	
Synthetic fuel production	**Hydrogen production**
Coal to gas without CCS Coal to liquids without CCS Biomass to gas without CCS 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 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*	Coal with CCS* Gas with CCS* Oil with CCS* 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 Efficiency	Electric Hydrogen* Efficiency*
Air	**Marine**
Biofuels in fuel mix Hydrogen planes* Efficiency*	Gas* Hydrogen* 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 (for auto-producers only) CCS in cement (for auto-producers only) CCS in chemicals (for auto-producers only)	
Agriculture	
Energy	**Other**
Biomass Electricity	
Non-CO2	
Enteric fermentation + Digester + Cogeneration (Agriculture)	Flare gas recovery + on site use
Waste water processing with recovery + cogeneration (Industry)	Flare gas recovery + compression + distribution

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4.9.7 Economic rationale and model solution

The modelling framework and solution rationale is similar to the MAPLE and NATEM models, as detailed for MAPLE in Section 4.6.7.

The TIMES-CAC model computes a dynamic inter-temporal partial equilibrium for the (multi-) regional energy and emission markets, based on the maximisation of total surplus defined as the sum of surplus of the suppliers and consumers. In other words, it is assumed that the multi-regional system evolves, while maintaining intra-temporal and inter-temporal partial economic equilibrium, and always occupies the technical possibility frontier. The process of solving the model determines the optimal mix of technologies (capacity and activity) and fuels at each period, the associated emissions, the mining and "trading activities", the quantity and prices of all commodities, all in time series from the base year to the time horizon of the model.

The model was mainly developed and used to assess the dynamics of the national energy system of the area in cooperative and non-cooperative manner, when energy export levels are determined by the willingness-to-pay of the different "importers/customers"[3].

The model responds to economic incentives (such as revenues from the exports) by optimising the domestic energy system (supply and demand of each energy form), the energy exchanges within the multiregional system (CAC area), and with the external markets, in an "integrated" manner. A "discount" factor of 5% per year is usually 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. Implicit discount rates are also used at sectoral level.

4.9.8 Key parameters

The TIMES-CAC model is "by paradigm" a technology-rich tool, where techno-economic information is assigned to each process (existing and future) of the system, and therefore many datasets/parameters can be extracted and reported.

Based on the geopolitical and strategic role of the CAC area in the international "energy" context, and on its specific technical and market characteristics that affect the local energy and climate plans, the following key information is selected as the "most important" parameters to monitor, discuss and evaluate in the framework of the PARIS REINFORCE project for a successful integration of this model with the other tools and analyses:

- Fossil fuel proven/possible reserves (mainly oil and gas) and expected production rates (P/R).
- Quantities and/or prices of trades (mainly for oil and gas), by area of import.
- Information about under construction/planned/possible energy projects/infrastructures.
- Burden/contribution of the countries/area to global climate targets (based on previous experiences, this is particularly relevant with respect to the gas allocation: domestic use vs. export), and national emission reduction goals.
- Energy efficiency improvements costs/limits (from the supply side to the demand side).
- Renewable energy and CCS costs/potentials.
- Local-specific priorities, targets, plans.

Parameters can be revised and updated in the framework of the PARIS REINFORCE project, following the feedback

[3] Model can currently run in two modes: with exogenously defined export levels per each direction of export, or with endogenously defined export levels through the most profitable route and destination. A risk-specific analysis can also be enabled to strategise the export of the region.

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of national experts (stakeholder engagement), the comparative assessment with other modelling experiences, and the discussion with the partners (modellers).

4.9.9 Policy questions and SDGs

4.9.9.1 Key policies that can be addressed

As for all the TIMES-based models, TIMES-CAC 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 or the explicit assignment of incentives);
- 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);

More in particular, TIMES-CAC is capable of exploring the direct economic advantage of cooperation policies in the energy and climate change mitigation sectors for the represented countries. The following cooperation policies in the area can be directly modelled:

- exploitation of Caspian oil and natural gas resources;
- investment in the construction of cross-national new pipelines;
- maintenance of free exchange in the energy sector across the region; and
- creation of a joint CO_2 emission permit system in the area.

Furthermore, the structure of the TIMES-CAC model allows to fully include the concept of "energy security" in the analysis (from the perspective of energy exporters), and to test the effects of long-term energy export strategies in the CAC region by exploring the trade-offs between a "risk" indicator and some key variables of the energy system such as the total cost, the quantities exported and the corresponding revenues, the climate targets of the region. Furthermore, (export) risk reduction goals can be combined with securing a minimum level of revenues from the hydrocarbon exports goals, with the aim to quantitatively evaluate the response of the energy sector and its sensitivity to different export strategies.

Table 4.19 provides additional information about the capability of the model to represent policies and measures per each key energy and climate dimension.

Table 4-19: Capability of the TIMES-CAC to address policies and measures

Policies and Measures (by dimension)[4]	Details
Decarbonisation	***High*** capability (several mitigation options, regulatory and economic measures, etc.)
Energy Efficiency	***High*** capability (several energy efficiency options, regulatory and economic measures, etc.)

[4] According to the new rules on governance of the EU energy union

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Energy Security	***High*** capability (key focus of the TIMES-CAC, risk and diversification targets)
Internal energy markets	***Medium*** capability (gasification of the systems, electrifications, partial/complete phase-out of fuel subsidies, etc.)
Research, Innovation and competitiveness	***Low-Medium*** capability (implicit and/or ex-post)

4.9.9.2 Implications for other SDGs

Apart from the abovementioned dimensions, a number of SDGs other than climate action can be taken into consideration and investigated making use of the TIMES-CAC model, as shown in Table 4.20.

Table 4-20: Capability of the TIMES-CAC consider/assess other SDGs

SDG	Details
§1. No Poverty (e.g., intra-country distributional impact by income level)	Trade-offs between energy poverty reduction (residential) measures vs. energy consumption can be partially explored.
§3. Health (e.g., air-pollution related mortality)	Measures to tackle the use of solid fuels in buildings (not negligible fractions in the CAC area, and direct cause of pollution-related mortality) can be included.
§7. Affordable and clean energy (e.g., traditional biomass use, %renewable energy)	Cost-effectiveness of RES within a specific storyline.
§8. Decent work & economic growth (e.g., impact on GDP per capita, jobs)	Energy export revenues can be tracked and analysed to evaluate the corresponding relevance/impact on the State budget (e.g. capability to fund RES, etc.) and on the domestic macroeconomic indicators.
§15: Life on land (e.g., land use for forests, rate of land use change)	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).

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4.9.10 Recent publications using the TIMES-CAC model*

Study	Focus	Key findings
Kerimray et al. (2018)	Long-Term Climate Change Mitigation in Kazakhstan in a Post Paris Agreement Context	Under the Paris Agreement, Kazakhstan's nationally determined contribution (NDC) target is to reduce its greenhouse gas emissions (GHG) by between 15 and 25% by 2030 compared with 1990 levels. Kazakhstan's energy system is highly carbon intensive and GHG emissions continue to steadily grow, indicating insufficient progress towards achieving the NDC emissions reductions announced under the Paris Agreement. This chapter presents modelling analysis that assesses a least-cost long term (2050) pathway towards achieving these NDC targets. The results demonstrate how ambitious a 25% GHG emissions reduction pathway is compared with the current energy policies and mitigation actions. Such a reduction requires an almost full phase-out of coal consumption in power generation by 2050.
Bakdolotov et al. (2017)	Techno-economic modelling to strategize energy exports in the Central Asian Caspian region	This paper studies the concept of energy security from export-oriented countries' point of view. It aims to test the effects of long-term energy export strategies in the Central Asian Caspian (CAC) region, by exploring the trade-offs between a "risk" indicator and some key variables of the energy system such as the total cost, the quantities exported, and the corresponding revenues. Risk reduction goals are combined with securing a minimum level of revenues from the hydrocarbon exports goals. It is also attempted to provide a definition and a quantification of a risk indicator on the basis of four components.
Kerimray et al. (2015)	Improving Efficiency in Kazakhstan's Energy System	There are various reasons for inefficiencies in Kazakhstan's energy system: administrative and economic (statistical double counting of energy flows, above normative losses and low profitability), geographic (the extremely continental climate and low population density) and technical considerations (high share of coal in generation mix, high wear on main and auxiliary equipment in energy intensive sectors, high wear on electric lines, dilapidation of housing stock, and an absence of control systems for energy savings) all contribute to the high energy intensity. This study explores energy efficiency potential by analysing the evolution of the Kazakh energy system. All the technical inefficiencies have been taken into consideration through the explicit representation of existing inefficient technologies/chains in a TIMES-based model. Under the assumptions of a market-oriented development of the economic system, even without specific policies (Business as Usual), the model suggests significant energy efficiency improvement: 22 Mtoe (million tons of oil equivalent) by 2030 and a 40 % reduction in energy intensity of GDP by 2030.
De Miglio et al. (2014)	Cooperation benefits of Caspian countries in their energy sector development.	This paper studies the development possibilities of the energy systems of four Central Asia and Caspian countries. It explores options that improve their domestic energy efficiencies and increase their export of fossil energy commodities. With the help of scenario analyses, it evaluates the direct economic advantage of improving the domestic energy efficiencies. Furthermore it calculates the direct economic advantage of cooperation. It finds out that a new/different geo-economic attitude brings USD billions of annual economic benefits, particularly if the countries aim to differentiate their export routes, increase the amount of export and contribute to climate change mitigation.

*or using national-specific analysis based on the utilisation of single-region tools inherited by the TIMES-CAC model

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4.9.11 References

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