PARIS REINFORCE

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D5.1 DOCUMENTATION OF NATIONAL/REGIONAL MODELS FOR EUROPE

WP5 – Transforming Europe

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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 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 national models for Europe, serving as a means of facilitating their participation in the co-creation process envisaged in the project.

3. Short summary of results (<250 words)

This document presents a good overview of the five modelling tools to be used in WP5 of the PARIS REINFORCE project. It has sufficient technical detail so that experts can have an accurate overview of the provided documentation.

All five models are EU and/or EU-national models, covering all EU Member States, but with different modelling approach, scope and capabilities. Two of the models, JET and LEAP, are energy system models able to depict in detail the energy supply side, through the characterisation of numerous technologies, and the energy demand side, thus provide a complete view of the energy sector at EU and EU-national level. ALADIN and FORECAST are detailed sectoral models, both using a bottom-up perspective. The former focuses on road transport and alternative vehicles, and the latter on the manufacturing and buildings sectors. Finally, a macroeconomic model, NEMESIS, provides socioeconomic evidence of a set of climate policy options.

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

4. Evidence of accomplishment

This report.

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Preface

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

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

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Executive Summary

This document presents the five modelling tools that will be used in WP5 of the PARIS REINFORCE research project. Its aim is to provide a good overview of each of the documented models for a large variety of stakeholders of climate policymaking within the European Union (EU). At the same time, it has sufficient technical detail so that experts can have an accurate overview of the provided documentation. For this purpose, the document is organised in two parts: firstly, a summary and comparison of the models and, secondly, a section that documents each model individually, providing a more in-depth overview.

All five models are EU and/or EU-national models, covering all EU Member States, but with different modelling approach, scope and capabilities. Two of the models, JET and LEAP, are energy system models able to depict in detail the energy supply side, through the characterisation of numerous technologies, and the energy demand side, thus provide a complete view of the energy sector at EU and EU-national level. Two other modelling tools, ALADIN and FORECAST, are detailed sectoral models, both using a bottom-up perspective. The former focuses on road transport and alternative vehicles, and the latter on the manufacturing and buildings sectors. Finally, a macroeconomic model, NEMESIS, provides socioeconomic evidence of a set of climate policy options.

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

The five models can be used synergistically, due to their different sectoral coverage. Consequently, it seems relevant to establish a linkage process between these tools which will, inter alia, take advantage of the specific strengths of each tool.

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Glossary

- **AFV**: alternative fuel vehicle
- **BAU**: business-as-usual
- **BEV**: battery electric vehicle
- **CAPEX**: capital expenditure
- **CCD**: cooling degree day
- **CCS**: carbon capture and sequestration/stockage
- **CDM**: clean development mechanism
- **CES**: constant elasticity of substitution
- **CHP**: combined heat and power
- **CNG**: compressed natural gas
- **CSP**: concentrating solar power
- **EEM**: energy-efficiency measure
- **ESR**: effort sharing regulation
- **ETS**: emissions trading system
- **EU**: European Union
- **EUA**: European Union Allowance
- **FCEV**: fuel-cell electric vehicle
- **GDP**: gross domestic product
- **GHG**: greenhouse gas
- **GJ**: gigajoule
- **GVA**: gross value added
- **HDD**: heating degree day
- **IAM**: integrated assessment model
- **ICT**: Information and communication technology
- **INDC**: intended nationally determined contribution
- **IPCC**: Intergovernmental Panel on Climate Change
- **ISCED**: international standard classification of education
- **LCOE**: levelised cost of electricity
- **LCOH:** levelised cost of heat
- **LEDS:** low emission development strategies
- **LNG**: liquefied natural gas
- **MEPS**: minimum energy performance standards
- **NPV**: net present value
- **OPEX**: operating expenses
- **PEV**: plug-in electric vehicle
- **PHEV**: plug-in hybrid vehicle
- **PV**: solar photovoltaic
- **RED**: renewable energy directive
- **REEV**: range-extended vehicle
- **RES**: renewable energy source
- **SDG**: sustainable development goal
- **SET Plan**: strategic energy technology plan
- **SLCF**: short-lived climate forcer
- **SSP**: shared socioeconomic pathway
- **TCO**: total cost of ownership
- **TED**: technology and environmental database
- **TRL**: Technology Readiness Level
- **VAT**: value added tax

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1 Introduction

Integrated Assessment Models (IAMs) are widely used for climate change analysis (Weyant, 2017). Generally, they are global models used for the comparison of different long-term scenarios, focusing mainly on mitigation options and, to a lesser extent, on climate change consequences (Nordhaus, 2017) or adaptation (Füssel, 2010)[1]. In PARIS REINFORCE, and among the diversity of the models to be used, five modelling frameworks will be employed to carry out analysis in Europe, at the EU/regional or national level: ALADIN, FORECAST, JET, LEAP and NEMESIS. This does not exclude models documented in D7.1 from analyses at the national and/or regional level within 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 WP5 analyses, according to their geographical granularity. Table 1 provides the main features of these five models.

- **ALADIN** is an agent-based simulation model of alternative fuel vehicles purchase decisions. The core aim of the model is to calculate the total cost of ownership for different drivetrains (e.g. gasoline, diesel, battery electric vehicle, plug-in hybrid vehicle for passenger cars, etc.) based on large datasets for individual user-driving behaviour and to determine the utility maximising options under various restrictions.
- **FORECAST** is a decision support tool aimed at scenario design and analysis of the long-term development of energy demand and greenhouse gas (GHG) emissions for the industry, residential and tertiary sectors at the national level in the EU. It is based on a bottom-up modelling approach considering the dynamics of technologies and socioeconomic drivers.
- **JET (or JRC-EU-TIMES)** is a multi-regional energy system model, designed for analysing the role of energy technologies and their contribution to meet Europe's energy and climate change related policy objectives. It models the uptake and deployment of technologies as well as their interaction with the energy infrastructure with an energy systems perspective.
- **LEAP** is a scenario-based energy-environment modelling tool. Its scenarios are based on comprehensive accounting of how energy is produced, converted and consumed in a given region or economy under a range of alternative assumptions on population, economic development, technology, price, etc.
- **NEMESIS** is a detailed applied macroeconomic model for the European economy. The model can deal with EU climate mitigation policies and especially focuses on different economic instruments and their economic impacts at EU, EU-national and sectoral level.

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

[1] Impact of climate changes and adaptation are less investigated because of larger uncertainties (Patt *et al.*, 2009; Pindyck, 2017).

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Table 1: Details of models for EU to be used in Work Package 5

		ALADIN	FORECAST	JET	LEAP	NEMESIS
Full name		ALternative Automobiles Diffusion and INfrastructure	FORecasting Energy Consumption Analysis and Simulation Tool	JRC-EU-TIMES	Long-range Energy Alternatives Planning System	New Econometric Model of Evaluation by Sectoral Interdependency and Supply
Type of model		Bottom-up sector perspective	Bottom-up sector perspective	Energy system model	Energy-Environment System	Macroeconometric model
Website		www.aladin-model.eu	www.forecast-model.eu	https://frama.link/hunjKQmf	https://frama.link/rTynpKFy	https://frama.link/r_Upbulb
Reference paper(s)		Plötz *et al.* (2014; 2019)	Fleiter *et al.* (2018), Herbst *et al.* (2017)	Simoes *et al.*, 2013 https://frama.link/LtNLAKRr	(Nieves *et al.*, 2019)	(Boitier *et al.*, 2018)
Team running the model		Fraunhofer ISI	Fraunhofer ISI	E4SMA	NTUA	SEURECO
Time horizon (final simulation year)		2050	2050	2060	2050	2050
Time steps in solution (years)		1	1	Flexible (up to 12)	Flexible (usually 1)	1
Regional granularity	**EU 28 as a whole**	Yes	Yes	Yes	Yes	Yes
	EU-28 Members state individually	All	All	All	All	All
	Other non-EU28 countries	Norway & Switzerland	Norway & Switzerland	Norway, Switzerland & Iceland (potentially: Balkans countries)	All (if consolidated dataset available)	
Sectoral granularity	**Macroeconomic**	No	Exogenous (as drivers)	Exogenous (as drivers)	Exogenous (as drivers)	Yes
	Agriculture	No	No	Energy requirements only	No	As economic activity
	Energy supply	No	No	Very detailed	Detailed	As economic activities with detailed technologies for power generation
	Industry	No	Very detailed	Detailed	Detailed	As economic activities
	Transportation	Detailed for road (passenger and freight)	No	Detailed	Detailed	As economic activities and Households expenditures
	Buildings	No	Detailed	Detailed	Detailed	As economic activities & Households expenditures
	Land uses	No	No	No	No	No

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2 What can this range of models for EU explore?

This diversity of tools is an asset for the PARIS REINFORCE project and, in order to make efficient use of them, we must inform on their potential uses for climate policy support. Evidently, not all questions can be equally addressed by all models, nor will all models that can address a specific question give similar answers. It should be noted that, although four models are based on detailed technological and sectoral approaches, the last one, NEMESIS, is a macroeconomic model that is a detailed sectoral model, but of which econometrics and granularity do not allow for an explicit characterisation of technologies. The policy issues to be addressed by the models are mitigation of GHG emissions and adaptation to climate change. However, the tools are better suited for studying mitigation options than they are for delving into adaptation.

This section begins with the presentation of the main drivers, or exogenous variables, such as socioeconomic assumptions or energy prices and others that are essential inputs for the modelling simulations. Once defined, the mechanisms involved in each model in the mitigation scenarios (and, for the JET model, some adaptation measures) are defined. After considering these drivers and mechanisms, we take stock of policy instruments that can be implemented in each model either directly or after specific modelling adjustments. We also look at the capability of the model outputs to track sustainable development goals (SDGs). Thereafter, we summarise how each model calculates a mitigation pathway. Finally, potential interlinkages are discussed, towards effectively exploiting the complementarities among the documented models and respective analyses.

2.1 Main drivers and socioeconomic assumptions

Before exploring the capabilities of the five models, we first present here the main drivers and exogenous assumptions necessary for the modelling simulations. All five models share a common set of drivers, namely GDP, population and fossil fuel price projections (except GDP in EU in NEMESIS, and population in ALADIN). The GDP and population projections are used to define the socioeconomic context, such as the shared socioeconomic pathways (SSP) scenarios (Riahi et al., 2017). The population projections should also consider the number of households (FORECAST, LEAP and JET) and household size (LEAP and JET), whereas, in the NEMESIS model, population projections should be characterised by age group and educational attainment level, as in SSP population projections (KC and Lutz, 2017). The sector-specific models require in addition more precise economic data than GDP projections. The FORECAST, JET and LEAP models require some projections of sectoral economic activities, and particularly for the industrial and tertiary sectors in FORECAST. Furthermore, the JET model also uses macroeconomic variables, such as private consumption to proxy the evolution of households' disposable income that drives their energy demand.

Beside socioeconomic assumptions, technological specifications[2] are also drivers of all five models, including for vehicle drive technologies in ALADIN (which also uses detailed datasets on drivers' profile and transport infrastructure availability); electricity generation in NEMESIS, process heat, machine drives, steam, and all other industrial processes in FORECAST and more generally all energy-related technologies in JET and LEAP.

[2] Technological specifications cover a large and diverse set of technologies according to the models. For instance, it can be investment cost of new nuclear power plant (per MWh) or the battery life of electric vehicles. A more detailed description of the technologies modelled in each model is available in section 3.

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Table 2: List of main drivers of the models

ALADIN	FORECAST	JET	LEAP	NEMESIS
• Cost of drive technologies (battery electric vehicles -BEV, range-extended vehicles -REEV, plug-in hybrids - PHEV, etc…) • Fuel prices • Drivers profiles (including trips purpose, length of route, departure and arrival time, etc.) • Transport infrastructures (charging)	• GDP • Population • Gross value added (GVA) • Industrial production for energy-intensive industry sectors • Number of employees in service sectors and industry • Square meter per employee in service sector • Number of households • End-consumer energy prices (electricity, coal, oil, natural gas, biomass, district heating) • Technology characterisation	• GDP • Population • Number of households • Households size • Private consumption or households' disposable income • Sectoral production growth • Technology characterisation • Fossil energy prices	• GDP • Population • Number of households • Households size • Sectoral economic activity growth (agriculture, etc.) • Demand in transports services (passenger-kms, tonne-kms) • Physical production growth in the industrial sectors • Fossil energy prices and biomass prices • Technology characterisation	• GDP for non-EU countries • Population by age groups and educational attainment level • Fossil fuels prices • Exchanges rates • Interest rates • Power generation technology specification

2.2 Mitigation and adaptation options in each model

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

Upstream technologies like hydrogen production and synthetic fuel production are mitigation options available in the JET model through electrolysis and biomass to liquid respectively. All models (except for ALADIN and FORECAST) cover a large set of mitigation options in the electricity and heat generation sectors, ranging from nuclear to renewables: hydro-electricity, solar photovoltaic (PV) and concentrating solar power (CSP), onshore and offshore wind turbine, biomass and geothermal, with the exception of nuclear, hydro and geothermal in NEMESIS, in which they are exogenously determined. Furthermore, carbon capture and sequestration/storage (CCS) technologies are also available mitigation measures in JET and NEMESIS, including coal, gas and biomass CCS. For heat generation, only JET and LEAP cover biomass and geothermal, but no CCS option is available.

In the buildings sector, the energy system models, FORECAST, JET and LEAP, cover a large range of climate change mitigation measures. The NEMESIS model includes mitigation options in the built environment as well, but these are less detailed. Finally, the FORECAST model includes a very high degree of detail for space heating and cooling and residential and tertiary sector appliances, allowing for in-depth analysis of mitigation measures in the European built environment.

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In the road transport sector, the ALADIN and JET models cover almost all mitigation measures, with a significant degree of detail in ALADIN in particular. LEAP and NEMESIS also cover numerous options (gas vehicles, electric vehicles or biofuels) except for hydrogen fuel cell vehicles in both models and hybrid electric vehicles in LEAP. The technological options for GHG emission reductions in aviation and shipping are relatively limited in all five models. The NEMESIS, LEAP and JET models allow biofuel substitution whereas electric engines are possible only in LEAP and JET. More precisely, biofuels, hydrogen, electricity and gas (for shipping only) are only available in the JET model, with a few modifications. Railways electrification is also available in JET, LEAP and NEMESIS. Finally, modal shift can be used to favour low-carbon transports, through exogenous assumptions, in JET, whereas in NEMESIS, the granularity of the model only allows modal shifts for households (distinguishing households' demand for road, rail, air and other transport services).

For the manufacturing sectors, the FORECAST model includes more than 80 processes and 200 different saving options allowing for an in-depth analysis of mitigation measures and pathways. JET and LEAP cover almost all mitigation measures listed in Table 5, except for hydrogen in process heat for the JET model and options for machine drives in LEAP. NEMESIS also covers different options but due to non-explicit technological specification, these are more limited.

To mitigate GHG emissions from agriculture, NEMESIS and LEAP cover emission reductions from energy use whereas, the JET model directly incorporates behavioural changes.

Finally, in all models and for all sectors, efficiency measures can be used as GHG mitigation options with a different degree of detail and mostly as exogenous assumptions in the NEMESIS model.

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

				ALADIN	FORECAST	JET	LEAP	NEMESIS
Mitigation measures	**Upstream technologies**	*Synthetic fuel production*				✓		
		Hydrogen production				✓		
	Electricity and heat generation technologies	*Electricity generation*	CCS			✓		✓
			Nuclear fission			✓	✓	✓[5]
			Hydro			✓	✓	✓[5]
			Biomass			✓	✓	✓
			Geothermal			✓	✓	✓[5]
			Solar PV & CSP			✓	✓	✓
			Wind onshore & offshore			✓	✓	✓
		Heat generation	Geothermal			✓	✓	
			Biomass			✓	✓	
	Buildings	*Heating*	Gas replacing oil / coal		✓	✓	✓	✓[2]
			Biofuels		✓	✓	✓	
			Electricity		✓	✓	✓	✓[2]
			Hydrogen			✓		
			Solar thermal		✓	✓	✓	✓[2]
			Building shell efficiency		✓	✓	✓	
			Other:		High degree of detail			
		Lighting	Efficient lighting		✓	✓	✓	
		Appliances	Efficient appliances		✓	✓	✓	
		Cooling	Electricity		✓	✓	✓	
			Building shell efficiency		✓		✓	
		Behaviour change (less energy service demand)			✓	✓[5]		✓

(1): Can be implemented by fuel prices; (2): Technology not explicitly modelled; (3): Can be added with some changes; (4): Only for households; (5): Exogenously determined; (6): In some sub-sectors (*e.g.* cement) (7): FORECAST also includes Ambient heat, (8): FORECAST also includes biomass.

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Table 4: Mitigation options in each model for transport

				ALADIN	FORECAST	JET	LEAP	NEMESIS
Mitigation measures	Transport	*Road*	Gas (LNG / CNG) vehicles	✓		✓	✓	✓(2)
			Hybrid electric vehicles	✓		✓		✓(2)
			Fully electric vehicles	✓		✓	✓	✓(2)
			Hydrogen fuel cell vehicles	✓		✓		
			Biofuels in fuel mix	✓(1)		✓	✓	✓(2)
			Efficiency	✓		✓	✓	✓(5)
			Other:	overhead catenary for heavy duty vehicles and				
		Rail	Electric rail			✓	✓	✓(2)
			Efficiency			✓	✓	✓(5)
		Aviation	Biofuels in fuel mix			✓	✓	✓(2)
			Hydrogen planes			✓(3)		
			Electric planes			✓(3)	✓	
			Efficiency			✓	✓	✓(5)
			Other:					
		Shipping	Gas (LNG / CNG)			✓(3)	✓	
			Hydrogen			✓(3)		
			Biofuels in fuel mix			✓	✓	✓(2)
			Electric			✓(3)	✓	
			Efficiency			✓	✓	✓(5)
		Modal shifts				✓ (5)		✓(4)
		Other behaviour changes (e.g. travelling less)				✓		✓

(1): Can be implemented by fuel prices; (2): Technology not explicitly modelled; (3): Can be added with some changes; (4): Only for households; (5): Exogenously determined; (6): In some sub-sectors (*e.g.* cement), (7): FORECAST also includes Ambient heat, (8): FORECAST also includes biomass.

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

				ALADIN	FORECAST	JET	LEAP	NEMESIS
Mitigation measures	Industry	*Process heat* [7]	Gas replacing oil / coal		✓	✓	✓	✓[2]
			Biomass		✓	✓	✓	✓[2]
			Hydrogen		✓		✓	
			Electricity		✓	✓	✓	✓[2]
		Machine drives	Gas replacing oil / coal		✓	✓		✓[2]
			Electricity		✓	✓		✓[2]
		Steam [8]	Gas replacing oil / coal		✓	✓	✓	✓[2]
			Electricity		✓	✓	✓	✓[2]
		CHP	Gas replacing oil / coal		✓	✓	✓	
			Biomass		✓	✓	✓	
		Overall industry	CCS		✓	✓[6]	✓	
		Other:			More than 200 different saving options plus innovative process technologies			
		Behaviour changes (lower material consumption)			✓	✓		✓
	Agriculture	*Energy use*	Gas replacing oil / coal				✓	✓[2]
			Biomass				✓	✓[2]
			Electricity				✓	✓[2]
		Behaviour changes (less product demand)				✓		

[1]: Can be implemented by fuel prices; [2]: Technology not explicitly modelled; [3]: Can be added with some changes; [4]: Only for households; [5]: Exogenously determined; [6]: In some sub-sectors (*e.g.* cement), [7]: FORECAST also includes Ambient heat, [8]: FORECAST also includes biomass.

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Table 6: Adaptation options in each model

			ALADIN	FORECAST	JET	LEAP	NEMESIS
Adaptation measures	*Land*	Water use restrictions			✓		
	Urban	Additional cooling of buildings			✓		
		Building material choices			✓		

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2.3 Policy instruments implementation

As reported in Table 7, four families of policy instruments (emissions mitigation, energy, land, and trade policy instruments) are covered by the different models.

Table 7: Mapping of policy options in each model

		ALADIN	FORECAST	JET	LEAP	NEMESIS
Emissions mitigation policy instruments	Tax	1	1	1	3	1
	Emissions target / quota (annual)	2	3	1	1	1
	Emissions target / quota (cumulative)	2	2	1	1	2
	Regulations (emissions standards, etc...)	2	1	1	1	2
	Financial supports (negative emissions, CDMs, Green Climate Fund)	2	1	1	1	2
Energy policies instruments	Tax	1	1	1	1	1
	Subsidy	1	1	1	1	1
	Energy mix target	3	2	1	1	2
	Efficiency target	2	2	1	1	2
	Regulations (thermal regulation in buildings, banning of diesel cars in urban areas, etc...)	2	1	1	1	2
Land policies instruments	Carbon sink pricing / Land use change emissions tax	3	3	2	3	3
	Afforestation targets	3	3	2	3	3
Trade policies instruments	Carbon border tax on imports	3	3	1	3	2
	Carbon border supports on exports	3	3	1	3	2
	Regulations policies (certifications, Best-available technologies, standards, etc...)	2	3	2	3	2

Legend:

1	Feasible
2	Feasible with modifications
3	Not feasible

Among the five emissions mitigation policy instruments listed in Table 7, all models can deal with carbon tax or carbon price (except for LEAP), with annual emissions targets or quota (except for FORECAST and with some adaptations for ALADIN), with multi-annual emissions targets or quota, regulations and financial support (with some modifications for ALADIN and NEMESIS).

The models also cover five energy policy instruments. All can implement energy taxation and/or energy subsidies and can fix an energy mix target (except for ALADIN and with some modifications for FORECAST and NEMESIS). Similarly, it is possible to fix efficiency targets in all models (but it will imply modifications in ALADIN, FORECAST and NEMESIS). All models (NEMESIS with some modifications) can use regulation instruments (e.g. norms), such as, thermal regulations in buildings or bans on diesel cars in urban areas.

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Two land policy instruments can be activated in the JET model if some modifications are done: a carbon sink pricing or land use change emissions tax and an afforestation target.

Finally, the JET and NEMESIS models can implement both carbon border tax on imports and carbon border support on exports (with some modifications for NEMESIS); while the implementation of trade regulation policies—based for instance on certifications, best available technologies or standards—can be incorporated in ALADIN and JET (assuming some modifications).

2.4 Analysis of other implications: the Sustainable Development Goals

Table 8 details fifteen of the seventeen SDGs set by the United Nations in 2015 for the year 2030. SDG13 on climate action, already investigated in the previous sections, and SDG17 on revitalising global partnership for sustainable development are excluded, as out of the scope of the featured modelling tools. Among these fifteen SDGs, the five models can deliver indicators to track directly or indirectly eight of the SDGs.

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

Measure	ALADIN	FORECAST	LEAP	JET	NEMESIS
§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					

The bottom-up models, ALADIN and FORECAST, are able to provide indirect measures related to SDG7, SDG9 and SDG12. ALADIN considers innovation in technology and infrastructure that can be useful for SDG9 (industry, innovation & infrastructure). More specifically, the FORECAST model can consider the detailed impact of innovation (superior to technology readiness level 5 - TRL5) on CO_2 emissions and energy demand for the industrial sectors, and can calculate the differential of investment between scenarios. FORECAST can deliver insights on SDG7 on affordable and clean energy, to the extent of considering potential use of renewables on the demand side. FORECAST can also give useful information for sustainable cities and communities (SDG11) by

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considering the impact of increased secondary production on CO_2 emissions and energy demand.

Both energy system models, LEAP and JET, are able to provide information for SDG6 on clean water and sanitation, by quantifying water consumption (and withdrawal for JET). Both are also well-designed to deliver several indicators related to SDG7 and particularly concerning renewable and clean energy sources. Furthermore, JET can mobilise a macroeconomic module (requiring some modelling adjustments), and provide GDP deviation between scenarios, which is useful for SDG8 (decent work and economic growth). JET quantifies system (energy-related) costs and investment needs that can be used to track SDG9, while it can also implicitly provide indicators related to the SDG11, considering the building stock and subsets of retrofit measures.

Finally, NEMESIS, as a macroeconomic model, is well-designed to provide indicators related to SDG8 on, for example, annual growth rate of real GDP per capita; annual growth rate of real GDP per employed person; average hourly earnings of employees or unemployment rate by educational level. NEMESIS also delivers indicators for SDG7, such as renewable energy share in gross inland energy consumption; energy intensity in terms of primary energy and GDP. As granularity of industrial economic activities is relatively large in NEMESIS, the model can give insights into SDG9, through indicators on manufacturing value added, manufacturing employment or CO_2 emissions per unit of value added. Finally, it can compute the labour share of GDP, a useful indicator for SDG10 on inequalities.

Beyond the capability of the five models to provide indicators for the SDGs, some are indirectly considered in the model through scenario assumptions or drivers. For example, NEMESIS takes into account, as drivers, the level of education attainment of the population, and therefore considers some aspects of SDG4 (on education) in its scenario design. Similarly, the JET model considers afforestation and exploitation patterns as input for renewable potentials, which are indirect elements of SDG15 (life on land).

2.5 How does each model calculate a mitigation pathway?

Since all five models are significantly different, they do not operate homogeneously to calculate climate change mitigation pathways. Furthermore, they are all limited by their geographical coverage (EU and EU-national) and some by a sectoral focus; therefore, they cannot directly deal with global climate change mitigation issues, such as limiting global warming to a target level.

The five models calculate mitigation pathway as follows:

- ALADIN projects the stock and total energy consumption and CO_2 emissions of road vehicles (passenger cars, as well as light- to heavy-duty vehicles) in scenarios. Thus, CO_2 mitigations can be calculated by comparison of scenarios with different policies.
- FORESCAST is a bottom-up simulation tool that calculates long-term scenarios for future energy demand and CO_2 emissions of individual countries until 2050 within a single model run. In the first step of the scenario process, an ambition level is determined qualitatively and quantitatively, which is then translated into important general and sectoral model parameters (e.g. CO_2 price, energy carrier prices, renovation rates, financial incentives for RES, etc.). After this first model setting, a scenario run is started. This is an explorative simulation approach considering the dynamics of technologies and socioeconomic drivers.
- LEAP is a scenario-based modelling tool, the climate module of which calculates changes in the atmospheric concentration of all implicated GHG emissions between a reference scenario (which depicts the current condition of a system in terms of energy—demand and supply—and demographics—population, income, etc.) and a number of GHG mitigation-oriented scenarios based on current and future

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limitations, aligned with the ongoing global treaties and agreements (such as the goals set by the Paris Agreement or by increasing ambition).

- JET is a scenario-based tool, which produces dynamic least-cost pathways subject to a number of environmental and technical constraints. The model allows the exploration of several mitigation policies, including targets (e.g. annual GHG emissions binding targets, cumulative carbon budgets), and sectoral/technology-specific policies (e.g. standards, subsides and taxes). Results provides country-specific implications for (*i*) the economy (including energy prices, investments in the energy system, marginal CO_2 abatement costs, etc.), (*ii*) the energy mix (fuels and technologies) and energy dependence, and (*iii*) the environment (in particular GHG emissions).
- NEMESIS uses a recursive-dynamic principle and is solved annually. Thus, the model can implement climate change mitigation policies on the basis of either annual GHG emissions constraints or a predetermined level of a climate policy instrument. In the first case, the model adjusts the level of the policy instrument, mainly a carbon tax, to reach the emissions target and, in the second case, the level of the policy instrument is predefined and the model calculates the related GHG emissions. In the case of an annual GHG emissions binding target, several modelling simulations can be done considering different pathways (under carbon budget constraint) and ranked according to the selected criterion.

2.6 Towards a more powerful modelling system: soft-linkage

The diversity and heterogeneity of the five models allow for covering a large set of mitigation options as well as policy instruments as detailed below. These tools will be used individually in the PARIS REINFORCE project, providing a large scope of quantitative outputs. There will exist some overlapping in the results of the models allowing for an enrichment of the analysis by comparing modelling outputs. However, the five models can be complementary also due to their different focus: NEMESIS covers macroeconomic aspects as inter-sectoral economic exchange; LEAP[3] and JET cover the entire energy system allowing for balancing between supply and demand and a detailed analysis of technological options; FORECAST provides for in-depth analysis of mitigation options in the industrial, tertiary and residential sectors; and ALADIN completes the puzzle with a very detailed analysis of alternative road vehicles diffusion. Thus, it seems very relevant to establish a linkage process between these tools trying (*i*) to provide a harmonised background for all five tools, (*ii*) to ensure coherency in the implementation of the tools and (*iii*) to take advantage of the specific expertise of each tool.

At this step, no formal linkage has been established and Figure 1 only draws a first attempt on how this linkage could be implemented. Starting from scenario storylines and related quantitative drivers that feed all models in a harmonised manner, macroeconomic indicators (such as GDP, households' disposable income, etc.) and sectoral economic activity will be calculated by the NEMESIS model and will be used as drivers in the others tools. In a first round, energy system models (JET and LEAP) will determine demand, supply and particularly energy prices of which the latter will be used as input for sectoral "energy-demand" models (FORECAST and ALADIN). From this first iteration, new energy demands from industry and buildings (FORECAST) and new vehicle fleets (ALADIN) are estimated and then used in energy-system models (JET and LEAP). When models' outputs converge[4], economic

[3] In PARIS REINFORCE, the LEAP model will be used for EU-national case studies, and particularly in Greece. Thus, linkage possibilities will be limited even if it does not imply that it will not be done.
[4] Convergence criteria will have to be defined later.

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variables (changes in investment requirements from energy supply and demand side, changes in energy expenditures, etc.) and new energy prices will be implemented in NEMESIS to assess the macro-sectoral impacts. A complete loop can be achieved when using new outputs of the NEMESIS model to feed the other modelling tools (ALADIN, FORECAST, JET and LEAP).

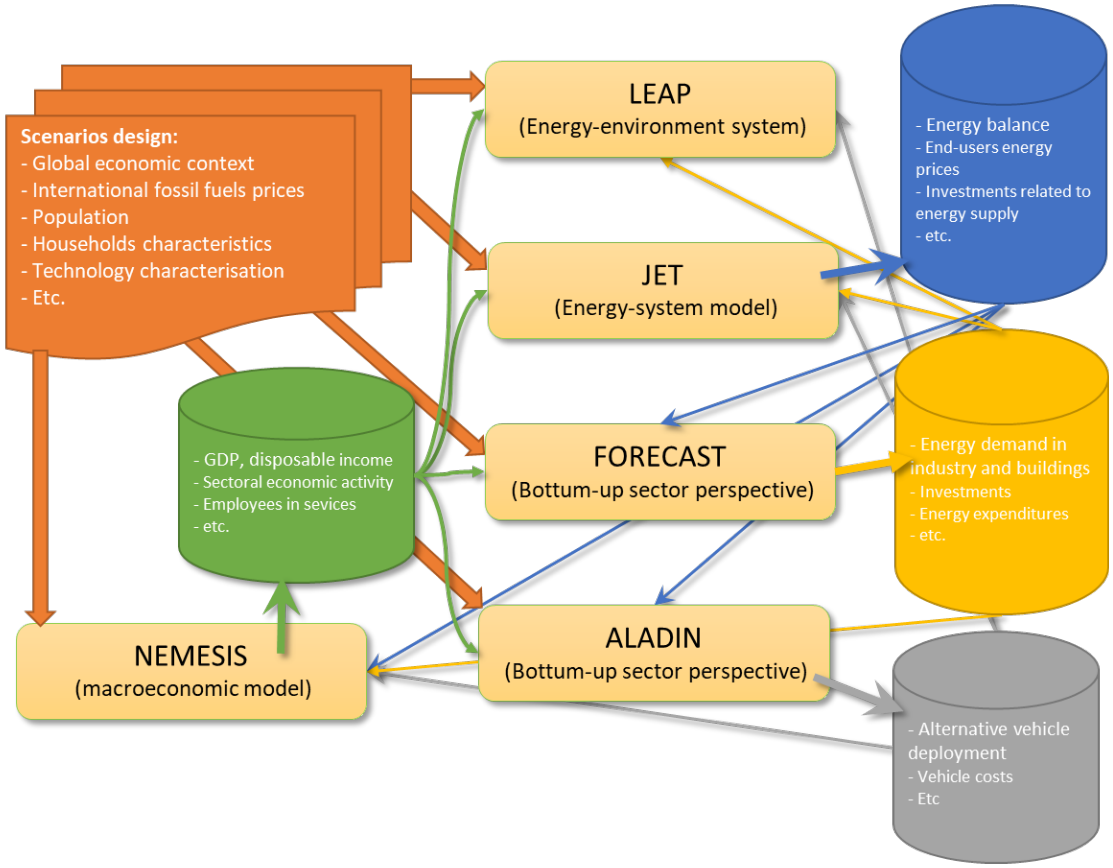

Figure 1: Illustrative scheme of potential linkages of WP5 models

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2.7 Examples use cases for the five models

Table 9: Examples use cases for the five EU models

Model	Example study(s)	Research question / focus	Selected key findings
ALADIN	Gnann *et al.* (2019)	Impact of public charging infrastructure for plug-in electric vehicles on their market diffusion	The paper demonstrates the possibility of a market diffusion in Germany without any slow public charging infrastructure until 2030. Although a charging point at home is obligatory for early adopters, the second-best option for an infrastructure set-up is at work.
	Plötz *et al.* (2019)	What can be the impact of catenary trucks on the European energy system?	We find that electric trucks can reduce CO_2 emissions from the transport and energy sector even when no additional renewable capacity is installed.
FORECAST	Heat Roadmap Europe (https://heatroadmap.eu/publications/)	What are EU heating and cooling strategies on national level for heating and cooling in Europe?	Heat savings can cost-effectively reduce the total heat demand in Europe by approximately 30-50%. Based on cost and energy considerations, district heating should increase from today's level of 10% up to 50% by 2050. Large heat pumps and other proven technologies can provide next generation district heating with renewable heat.
	REFLEX (publication available in 2020 - www.reflex-project.eu)	What are future flexibility potentials in a low-carbon EU energy system and how can they cope with future flexibility needs for RES integration?	Electrification and the use of H_2 are promising decarbonisation options for transport and industry sectors. On the demand-side, the diffusion of decentralised batteries as part of PV systems and in electric vehicles as well as H_2 production by electrolysers could provide necessary flexibility for the electricity system.
LEAP	Martínez-Jaramillo *et al.* (2017)	How much GHG emissions could be avoided by the implementation of planning strategies for the Medellin metropolitan area between 2010 and 2040?	The results indicate that a policy combining the promotion of mass transportation could represent 5.65 Million Tons of CO_2 equivalent avoided by 2040 (a 9.4% reduction).
	Emodi *et al.* (2017)	What are the future GHG emissions in Nigeria in 2040?	It is observed that in the Green Optimistic scenario the emissions will be 11% lower than in the reference scenario.
JET	Sgobbi *et al.* (2016)	What can be the role of H_2 production in a low carbon energy system sustainable future power system?	The paper indicates hydrogen could become a viable option already in 2030, however, a long-term CO_2 cap is needed to sustain the transition. Low-carbon hydrogen production technologies dominate, and electrolysers provide flexibility by absorbing electricity at times of high availability of intermittent sources.
	Paardekooper *et al.* (2018)	How effectively support the decarbonisation of the heating and cooling sector in Europe and democratise the debate about the sector?	The report indicates that the European Union should focus on implementing change and enabling markets for existing technologies and infrastructures in order to take advantage of the

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			benefits of energy efficiency in a broader sense and for the heating and cooling sector specifically.
NEMESIS	Muller *et al.*, (Forthcoming)	How much can carbon border adjustments reduce the costs for EU of a unilateral climate change mitigation policy?	The implementation of a tax on the carbon content of EU importations can reduce the negative impacts of stringent GHG mitigation policies, within the EU, on competitiveness and furthermore with more positive effects when incomes from this tax are redistributed.
	France Stratégie (2019)	What is the social value of carbon in France?	The report recommends, for 2030, to put forward a shadow price of €250/tCO_2. By 2050 it is expected to align with the estimated costs of the enabling technologies required for decarbonisation — therefore a cautious range of €600 to €900/tCO_2.

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3 Detailed documentation of each model

3.1 ALADIN - ALternative Automobiles Diffusion and INfrastructure

3.1.1 Short overview

ALADIN is an agent-based simulation model for assessing the market diffusion of alternative fuel vehicles (AFV). The acronym ALADIN stands for ALternative Automobiles Diffusion and INfrastructure. To date, the simulation comprises the market diffusion of passenger cars and heavy-duty vehicles in Germany and Europe until 2050. The simulation is based on driving data of several thousand individual vehicles that are treated as agents purchasing new vehicles. Changes in prices, user preferences, and model availability lead to market evolution for fuels and vehicles in road transport.

3.1.2 Methodology

3.1.2.1 Model core for Germany

The simulation model ALADIN calculates the market diffusion of AFVs based on a comparison of the economic efficiency of different drive systems and considering obstructive and supportive factors for approximately 6,500 driving profiles. The successive approach allows the effects of individual influencing factors on market evolution to be analysed separately and thus makes it more transparent.

The costs of buying and using a vehicle of course play an important role for potential buyers when making a purchasing decision. In commercial fleets, the economic aspects are even more important. Compared to conventional cars, AFV are generally more expensive to purchase, but they are often cheaper to run because of lower fuel and maintenance costs, among other things. It is therefore essential to look at costs in terms of the total use, in order to determine for which utilisation or driving profiles electric cars are more economical than conventional ones. Total cost calculations for vehicles are correspondingly a common component of models of market penetration of electric vehicles.

The model consists of three basic steps (Figure 2). In a first step, the costs of total use, referred to as TCO (Total Cost of Ownership), are ascertained for alternative and conventional vehicles. The TCO comprise the purchase and operating costs for the respective vehicle and are calculated from a user's perspective. Three user groups are distinguished—private, commercial (only fleet vehicles) and company cars—because of their different rates of taxation and depreciation options as well as their deviating patterns of utilisation. Because the TCO are also strongly influenced by the size of the vehicle, different car segments are also distinguished.

The drive technologies analysed included battery electric vehicles (BEV), plug-in electric vehicles (PEV), range-extended vehicles (REEV), plug-in hybrids (PHEV), CNG vehicles and fuel-cell electric vehicles (FCEV) as well as conventional gasoline and diesel vehicles. For the TCO calculations, the cheapest respective drive technology is selected.

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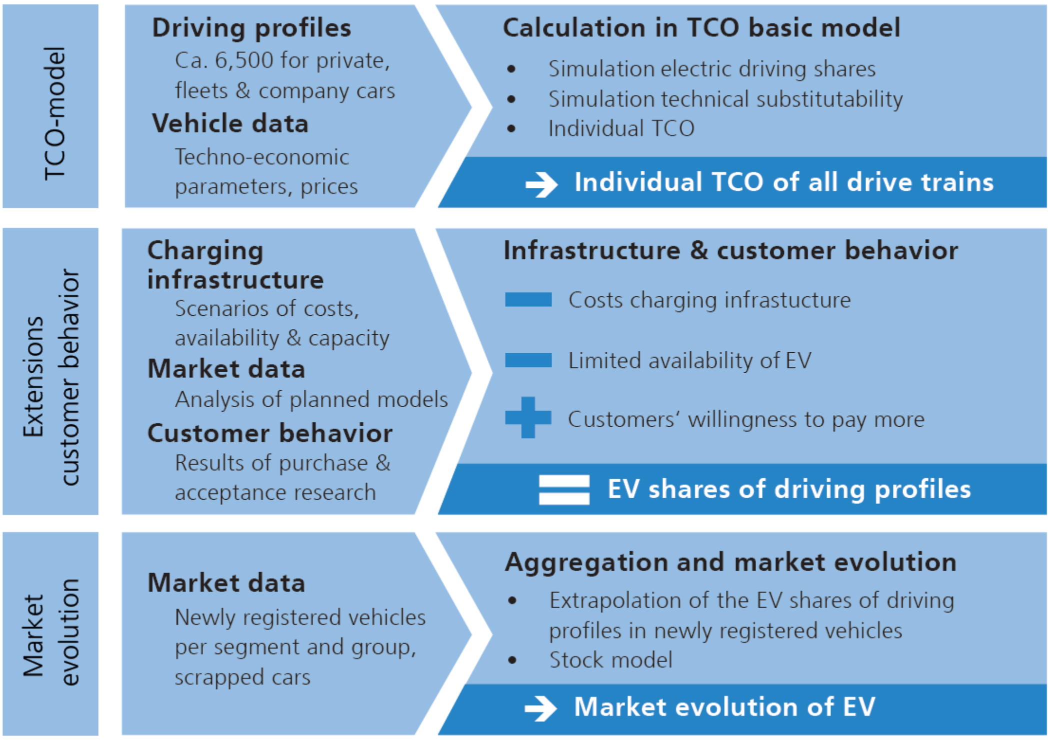

Figure 2: General structure of the ALADIN model.

One of the key innovations of ALADIN compared to previous TCO analyses is that the calculations are not made based on average annual mileages but are instead based on real-life driving profiles. A driving profile covers all the trips including the purpose, length of route, departure and arrival time, duration as well as information about the vehicle over an observation period of at least one week. Profiles vary widely by user even within the different groups and have a very strong influence on the economic efficiency of electric vehicles. The barrier presented by BEV's limited range is explicitly considered in the analyses; each individual driving profile is analysed according to whether the driver is able to make all the trips with a BEV. In addition, the electric driving share of PHEV or REEV is simulated individually for each driving profile. This is important to obtain realistic results on economic efficiency, which depends on the share of electric driving and is especially relevant for PHEV and REEV. The first step, therefore, is to make TCO calculations on this basis.

In the second step, the TCO calculations are extended by including the costs of the main charging infrastructure. This is done in order to put the assessment of the economic efficiency in the TCO calculations on a broader basis. Charging infrastructure costs vary widely depending on the charging type and location. For instance, using private charging infrastructure is generally cheaper for drivers with a garage than for drivers using public charging infrastructure, on which on-street parkers have to rely. Because the methodology is a simulation which does not represent spatial modelling but only trip purposes (such as for example "going home", "going to work", "going shopping"), statements about the infrastructure are only possible to a limited extent. The infrastructure assumption made is the same for all users in the respective user group. Depending on the scenario, car users are provided with a different amount of charging infrastructure (for example, only charging at home for private users and only charging at work for commercial users). In terms of costs, however, only the primary charging point (*e.g.* the private wall box of garage owners) is classified.

The brand and size of a vehicle are also important factors influencing the decision to buy. For instance, many buyers are extremely loyal to a particular brand. There will continue to be a restricted range of models and brands

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of electric vehicles available in the near future, which represents a limiting factor for the market evolution of electric vehicles. The restricted choice and availability of brands are therefore taken into account in the model. This is done by analysing currently offered models of electric vehicles and the announcements made about planned new ones. Logistic growth in the number of available makes with BEV or REEV/PHEV drives is then determined on this basis using ordinary least squares regression. It is also assumed that some buyers decide in favour of an EV of a different brand (if an EV has ideal TCO) and the rest for a conventional vehicle of the original brand. The most important factors obstructing market diffusion of electric vehicles are taken into account with the economic efficiency, range anxiety and limited offer of electric vehicles.

The fourth and final step then integrates other aspects of electric vehicles, which tend to support their market penetration, for example environmental friendliness, low noise emissions or the allure of an innovative technology. These supportive aspects are integrated in the model for private users via the willingness to pay more. Experience shows that the admission of a willingness to pay a higher price in questionnaires is not the same as actually observed purchasing behaviour. Nevertheless, it does provide first indications of the esteem attached to new technologies and the approximate magnitude of the willingness to pay more for them. The approach of taking the willingness to pay a higher price is a common one in market diffusion models of AFVs.

In this final step, the market evolution is modelled for AFV in Germany up to 2050. The driving profiles at which an AFV becomes economically viable are determined for each year based on the analyses conducted. The evolution of the market is then determined by extrapolating the share of these users in newly registered vehicles. Monetary policy measures are also integrated into the model such as purchase bonuses, for example, and their impacts on the evolution of the market are quantified.

3.1.2.2 Passenger Cars outside of Germany

The market diffusion of passenger cars in Europe is based on the projected diffusion in Germany and combined with country specific factors. We fit logistic functions to model-based predictions for Germany, for the period 2017-2030 and transfer them to the other European countries with modifications according to the national electricity and gasoline price ratio. The basic rationale is to use current market shares as starting point and modify the logistic market diffusion according to national conditions. These conditions, when expressed in savings per kilometre between conventional and PEVs, vary between €0.03 and €0.08 per km (between countries that combine less electricity prices with high gasoline prices or vice versa). These country specific fuel savings are used to set the growth parameter of a logistic diffusion curve. The second parameter of the diffusion curve, the time with 50% market diffusion, is set such that the logistic market diffusion curve meets the countries 2016 PEV sales share. We thus arrive at country specific logistic market diffusion curves of PEV that are projected until 2050.

3.1.2.3 Heavy-duty vehicles

We calculate sales and stock for AFV heavy duty vehicles until 2030 for Germany and extrapolate market shares until 2050. The reason for the extrapolation is that the extrapolation of market shares provides higher certainty than extrapolating the forecasts for individual parameters in long-term forecasts. The calculated market shares are considered equal in all other European countries as we assume a coordinated European infrastructure ramp up and heavy road transport is to a large extent trans-national in Europe. For catenary hybrid trucks, the share of electric driving with trolley trucks depends on the share of highways with overhead lines and the annual driving distance of the truck (the average share of km on the highway increases with annual vehicle km travelled). We assume that connected highway segments with the highest heavy-duty traffic will be electrified first. In many cases, the distribution of highway traffic is right skewed. Accordingly, the relation between the share of electrified vehicle kilometres and electrified highway kilometres is modelled mathematically.

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3.1.2.4 Input Data

The driving profiles of vehicles form a very important foundation for the calculations. A separate database ("REM2030-Fahrprofile") is used for commercial traffic (fleet users) and the so called "Mobility Panel" for private and company car users (MOP), which also contains information about the driver that can be used to distinguish private users with privately owned vehicles from those with a company car. The driving data only covers Germany, but general driving patterns do not vary much within Europe, only the total distance travelled (in million passenger km or average annual of vehicle kilometres travelled). The influence of the charging infrastructure can also be modelled to a certain extent using the driving profiles, because the driving profiles of the mobility panel contain information about the trips made. As already discussed, no spatially resolved modelling is done. A willingness to pay more is assigned to each individual private driving profile according to the affiliation to one of four groups in the innovation process. Based on a cross-comparison of the different studies, it is assumed that 55% of commercial users are not willing to pay more. The other 45% have a willingness to pay 10% more on the so-called Full Leasing Rate. In the market evolution model, this is translated as an extra 7% on top of the purchase price of the conventional reference model. Overall, the assumptions about the willingness to pay more are rather cautious compared to the statements made in the underlying studies. As already stated, company car users are assumed not willing to pay more. In ALADIN, only 1.5% of the driving profiles are assigned a willingness to pay of more than 10%, and approximately half of the private driving profiles are given a low willingness to pay 1% more. The willingness to pay more is assumed to decrease to 60% by 2020 and further thereafter for both private and commercial users, because novel technologies become less attractive over time.

Driving date for medium and heavy-duty vehicles is taken from the large-scale commercial vehicle survey KiD 2010 for Germany. It is enriched with transport performance and annual mileage data from EUROSTAT.

3.1.3 Model coverage

3.1.3.1 Geographical, temporal, and segment coverage

The ALADIN model covers Germany and Europe (individual EU28 countries as well as Switzerland and Norway). It simulates the market diffusion of AFVs from 2011 until 2050. Focus of the analysis are passenger cars, as well as light-duty, medium-duty and heavy-duty vehicles. Additional model runs cover the US, China, and India.

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Focus of research with ALADIN

	Passenger cars	Heavy-duty vehicles	Inland & Deep-sea navigation; Aviation
German regions (NUTS3)	Diffusion of Alternative Fuel Vehicles Local Energy Demand	Diffusion of Alternative Fuel Vehicles Local Energy Demand	Diffusion of alternative fuel ships in inland navigation
Germany	Diffusion of plug-in electric vehicles Diffusion of fuel-cell electric vehicles Influence of charging infrastructure Energy system analysis	Diffusion of catenary hybrid vehicles, fuel-cell electric vehicles, natural gas vehicle, plug-in electric vehicles Influence of catenary infrastructure Energy system analysis	Diffusion of Alternative Drive Trains from Traffic starting in Germany
Europe	Diffusion of plug-in electric vehicles Energy system analysis	Diffusion of catenary hybrid vehicles Energy system analysis	
EU, US, CN, IN	Diffusion of Alternative Fuel Vehicles Local Energy Demand	Diffusion of Alternative Fuel Vehicles Local Energy Demand	

Figure 3: Coverage of the ALADIN model

3.1.3.2 Mitigation options

The model covers the PEV, BEV, PHEV, REEV, CNG, and FCEV as mitigation options in road transport for passenger cars. The model can incorporate the change in energy, vehicle, or battery prices directly. Changes in general car usage or purchase, such as the increased usage of car sharing, must be integrated as changes in total passenger car sales. Furthermore, modal shifts can be integrated indirectly too, *e.g.* as reduction in annual mileage of the vehicles or lower total number of vehicles sold. One strength of the model is that an increased availability of public charging infrastructure can be directly modelled.

For medium and heavy-duty vehicles, the ALADIN model covers BEV, PHEV, FCEV, and catenary hybrid trucks as mitigation technologies. An increase in charging or refuelling infrastructure can be directly modelled in ALADIN, whereas a total change in freight activity must be incorporated as reduced vehicles sales or change in annual mileage.

3.1.4 Specific modelling for PARIS REINFORCE

With help of the ALADIN model, the PARIS REINFORCE project will analyse the following transport specific aspects in Paris Reinforce:

- electrification strategies for passenger cars and heavy-duty vehicles;
- infrastructure evolution for refuelling/recharging of AFVs;
- policies targeting AFV investment decisions;
- real-life behaviour and modal shift; and
- comparisons between electrification in road transport and the introduction of synthetic fuels in air and water transport.

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3.1.5 Recent publications using the ALADIN model

Table 10: List of recent publications using the ALADIN model

Paper	Topic	Key findings	Linkage with other modelling tools
Gnann *et al.*, 2019	Effect of slow charging infrastructure on PEV sales	How much public charging infrastructure for PEVs is needed and is there mutual interaction in the diffusion of public charging infrastructure and electric vehicles? The paper demonstrates the possibility of a market diffusion in Germany without any slow public charging infrastructure until 2030. Although a charging point at home is obligatory for early adopters, the second-best option for an infrastructure set-up is at work where the majority of vehicles is parked for a long time during the day, installation is not costly and users profit more than from public facilities.	No
Plötz *et al.*, 2019	Impact of Catenary trucks on energy system	Market diffusion scenarios of electric trucks in Europe are studied, while covering CO_2 emissions from trucks in the transport and energy sector. We introduce load curves for trolley trucks and run a complete energy system analysis including trolley trucks. We find that electric trucks can reduce CO_2 emissions from the transport and energy sector even when no additional renewable capacity is installed.	Yes (with the energy system model PERSEUS-EU)
Gnann *et al.*, 2018	Load shifting and RES integration potential of electric vehicles	We model the market diffusion of electric vehicles and their load shifting potential. We analyze private and commercial PEVs in Germany in 2030 with 50% renewables. Commercial electric passenger cars charge different to private ones. We find large load shifting potentials if charging at home and at work is possible. 25–30% more excess renewable electricity can be integrated with PEV load shifting.	Yes
Gnann, 2015	Market diffusion of electric vehicles and their charging infrastructure	Analysis of electric vehicles market diffusion scenarios in Germany until 2030 and interaction with public charging infrastructure roll-out. We find that there is no chicken-egg-problem for charging infrastructure for electric vehicles in western Europe as most users can easily charge at home. Furthermore, additional public slow charging infrastructure has hardly any effect on electric vehicle sales	No
Kluschke *et al.*, under review)	Market diffusion of Fuel cell trucks in Germany and optimal H2 fuel station network	The paper describes market diffusion scenarios for FCEV trucks in Germany. It develops a model for the optimal siting and number of the refueling network with capacity limits as important property of hydrogen fuel stations. We find about 160 – 350 Hydrogen refueling stations to cover heavy-duty highway transport in Germany. A capacity limit per station increases the number of stations required and changes their optimal location.	Yes

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3.2 FORECAST - FORecasting Energy Consumption Analysis and Simulation Tool

3.2.1 Short overview

The FORECAST model is designed as a tool that can be used to support strategic decision making. Its main objective is to support scenario design and analysis for the long-term development of energy demand and GHG emissions for the industry, residential and tertiary sectors at country level. FORECAST considers a broad range of mitigation options to reduce CO_2 emissions, combined with a high level of technological detail. It is based on a bottom-up modelling approach considering the dynamics of technologies and socioeconomic drivers. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways. The model further aims to integrate different energy efficiency and decarbonisation policy options and allows to address research questions related to energy demand including the analysis of scenarios for future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and impact on GHG emissions as well as abatement cost curves, ex-ante policy impact assessments and the investigation of long-term sustainable energy transition scenarios (Fleiter *et al.*, 2018 and Herbst *et al.*, 2017).

3.2.2 Key features of the FORECAST model

3.2.2.1 Model structure

The FORECAST platform comprises **three individual modules** (see Figure 4), each representing one sector according to the Eurostat energy balances: **industry, services/tertiary and residential**. While all sector modules follow a similar bottom-up methodology, they also consider the particularities of each sector like technology structure, heterogeneity of actors and data availability.

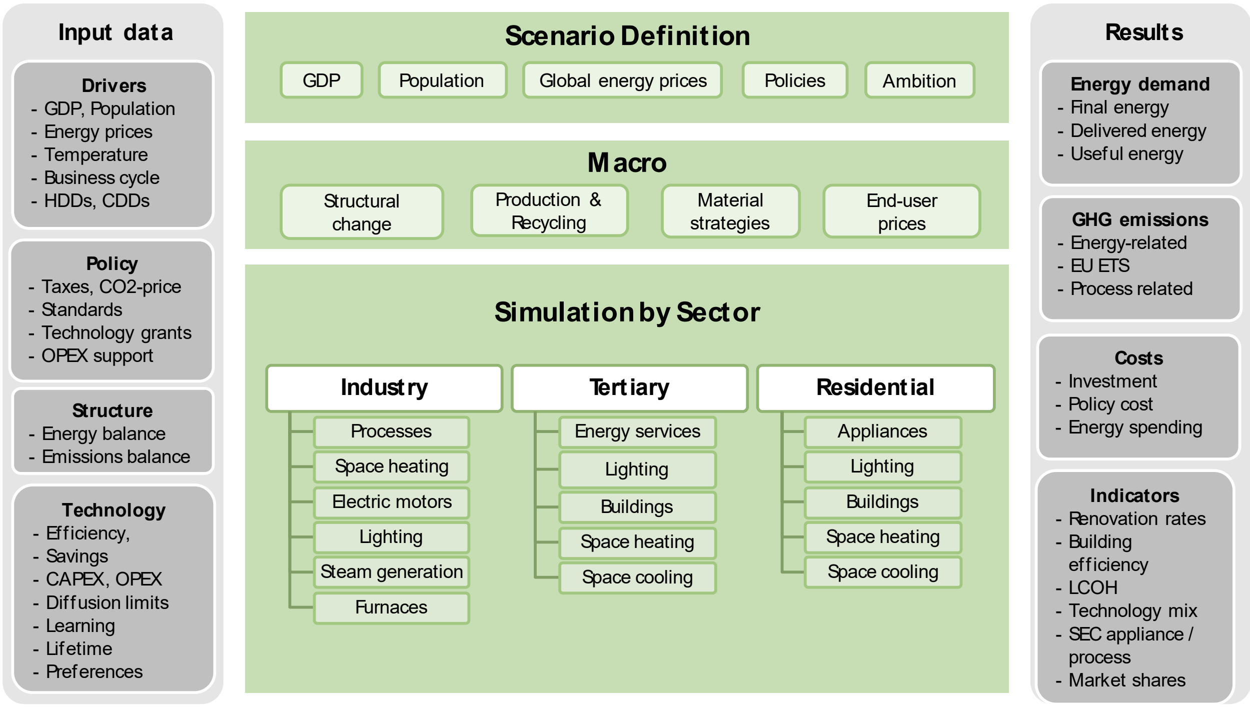

Figure 4: Overview of the FORECAST model structure

Source: FORECAST

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The list of selected **input data** provides an idea of the level of detail of each module. Each sector requires sector specific **activity data**, like industrial production in the industry sector, number of employees in the services sector and number of households in the residential sector. These can either be retrieved from external sources or derived within the macroeconomic module of FORECAST, based on available GDP and population projections from other models or studies. Furthermore, end-consumer **energy prices** play an important role in each sector and are distinguished by energy carrier (*e.g.* electricity, coal, oil, natural gas, biomass and district heating). These too can either be retrieved from external sources or derived within the macroeconomic module of FORECAST based on available wholesale price projections for electricity, coal, oil, and natural gas. The third group of input data, the **technology characterisation** also reflects data availability of the individual sectors. While in the industry and tertiary sector the model works with so-called energy-efficiency measures (EEMs), which represent all kinds of actions that reduce energy consumption, in the residential sector the stock of alternative appliances and the market share of different efficiency classes is explicitly modelled. In all cases, energy savings can be calculated and traced back to technological dynamics including cost considerations.

3.2.2.2 Geographical coverage and time-horizon

The model system has been developed for the **EU-28 plus Norway and Switzerland**, but has also been applied in international studies for Turkey, Brazil and Taiwan (Bastos *et al.*, 2017; Huang *et al.*, 2016 and Elsland *et al.*, 2014). The model delivers **annual results** at **country-level up to 2050**.

3.2.2.3 Model result granularity

As an outcome of the bottom-up approach modelling results can be disaggregated with a very high resolution, comprising sectors and sub-sectors, but also end-use technologies and energy carriers. Examples for these fields are shown in Figure 5.

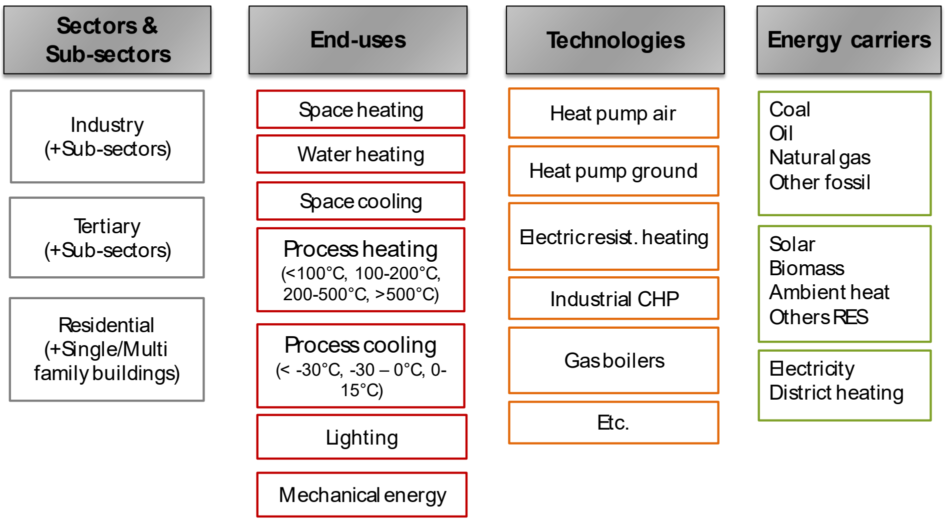

Figure 5: Disaggregation of FORECAST results

Source: FORECAST

A list of technologies considered in the model is provided in Table 11, showing its high level of technological detail. FORECAST considers all major tertiary and household appliances and a large variety of different heating technologies for buildings (also by sub-sector). In the industry sector, in addition to the differentiation by sub-sector and energy carrier, the most important energy-intensive products are implemented in the model and further differentiated by production process. Depending on data availability, processes can consist of small

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individual production steps (*e.g.* burning of clinker in the cement industry) or entire production lines for individual products or product groups (*e.g.* bricks, ceramic tiles).

Table 11: Technology detail in FORECAST

Industry	Buildings (tertiary and residential)	Appliances (tertiary and residential)
Energy intensive products	**Buildings**	**Residential appliances**
– Steel	– Single family	– Lighting
– Aluminium	– Multi family	– Refrigerators and Freezers
– Copper	– Commercial	– Washing machines and Dryers
– Cement	**Space heating**	– Dishwashers
– Paper	– Electric radiator	– TV
– Pulp	– Coal boiler	– IT
– Flat glass	– Lignite boiler	– Space cooling
– Ethylene	– Natural gas boiler	– Cooking
– Ammonia	– Oil boiler	– Circulation pumps
– Methanol	– Solar thermal plus others	– Others
– Chlorine	– Biomass boiler	**Tertiary sector appliances**
– ...	– District heating	– Lighting and street lighting
Steam generation	– Heat pump	– ICT office and ICT data centres
– Boilers (electric, gas, etc.)	– Combined heat and power (CHP)	– Ventilation and air-conditioning
– Steam and Gas turbines	– Night storage heating	– Circulation pumps
– Fuel cells		– Elevators
– Large heat pumps		– Cooking
– Internal combustion engines		– Laundry
Electric motor systems		– Refrigeration
– Pumps		– Misc. building technologies
– Fans		– Cooling in server rooms
– Compressed air		
– Machine tools		
– Process cooling		
– Other motors		
Lighting		
Space heating and cooling		

Source: FORECAST

The production of steel, for example, is differentiated in: coke oven, sinter, blast furnace and converter, electric arc furnace, H2 plasma (steel), DR H2 + EAF (steel), DR electrolysis (steel), DR natural gas (steel) and rolled steel. In total, FORECAST currently considers more than 80 processes and 200 different saving options are modelled in the industry sector.

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3.2.3 Methodology

3.2.3.1 Industry

The industry model distinguishes nine sub-sectors (iron and steel, non-ferrous metals, paper and printing, non-metallic minerals, chemicals, food and drink and tobacco, engineering and other metal, other non-classified, and refineries), more than 80 process technologies and a variety of cross-cutting technologies. The main macro-economic drivers are industrial production[5] for basic material products, gross value added for less energy-intensive sub-sectors and employment numbers. Five sub-modules cover: basic materials processes, space heating, electric motor systems, furnaces and steam systems. For each process, saving options are defined, reducing the specific energy consumption and process-related GHG emissions by diffusing through the technology stock. Diffusion depends on boundaries and payback time. The payback time in turn is determined by end-consumer energy prices, European Union Allowance (EUA) prices and the saving potential (for details see Fleiter *et al.*, 2018).

3.2.3.2 Tertiary

The tertiary model distinguishes eight sub-sectors (trade, hotel and restaurants, traffic and data transmission, finance, health, education, public administration and other) and various end-uses as shown in Table 11. To derive future energy demand, an annual energy service driver is multiplied by the annual specific energy demand per unit of driver. For example, the electricity demand for space cooling can be calculated using the specific energy demand per m^2 floor area cooled and the quantity of the given driver, here the share of cooled floor area per employee. This is in turn driven by employment in the tertiary subsectors. The diffusion of energy efficiency measures depends on the cost-effectiveness of efficiency alternatives or efficiency add-on measures (see section 3.4; for more details see Jakob *et al.* (2012) and Jakob *et al.*, 2013).

3.2.3.3 Residential

The residential model separates household energy demand into four sub-groups (appliances and lighting, sanitary hot water, space heating, new and others), which are reflected by various end-uses (see Table 11). The end-uses are further broken down into technologies, and each technology is distinguished by various efficiency classes. The calculation of energy demand in the residential sector is structured as follows: the majority of final residential energy demand is attributed to space heating. The useful heat demand is calculated in a first step based on a detailed representation of the European building stock. The model is designed as a vintage stock model that captures the number of end-uses in the market in combination with their age distribution. For heating systems, the vintage stock is represented by market shares. Technology diffusion depends on the relative cost advantages of substitution alternatives. The cheaper an alternative is, the larger its market share in the corresponding year (for details see Elsland, 2016).

3.2.3.4 Modelling investment decision

The bottom-up approach, which distinguishes individual technologies, allows modelling the diffusion of technologies as the result of individual investment decisions taken over time. For all types of investment decisions, the model follows a simulation approach rather than optimisation in order to better capture the real-life behaviour

[5] The physical production projections are carried out in the macroeconomic module of FORECAST considering trends to higher gross value added, material efficiency, material substitution and recycling.

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of companies and households.

Whenever possible, the investment decision is modelled as a discrete choice process, where households or companies choose among alternative technologies to satisfy a certain energy service. It is implemented as a logit approach considering the total cost of ownership (TCO) of an investment plus other intangible costs. This approach ensures that even if one technology choice is more cost-effective than others, it will not gain a 100% market share. This effect reflects heterogeneity in the market, niche markets and non-rational behaviour of companies and households, which is a central capability to model policies. Still, the resulting technology development (and energy demand) is price sensitive.

The replacement of equipment/buildings/technologies is based on a vintage stock approach allowing to realistically model the replacement of the capital stock considering its age distribution. Some parts of the industrial and the tertiary sector are not using a vintage stock approach, due to the huge heterogeneity of technologies on the one hand and data scarcity on the other. Technology diffusion, however, is modelled based on a similar simulation algorithm taking heterogeneity and non-rational behaviour into account.

3.2.3.5 Modelling policies

Modelling energy-efficiency policies is a core feature of the FORECAST model. The simulation algorithm and the vintage stock approach are well suited to simulate most types of policies.

Minimum energy performance standards (MEPS), *e.g.* for appliances or buildings, can easily be modelled by restricting the market share of new appliances starting in the year the standards come into force. See Elsland *et al.* (2014) and Jakob *et al.* (2013) for examples of ex-ante impact assessments of the EU-Ecodesign Directive.

Energy taxes for end-consumers can be modelled explicitly on the basis of more than ten individual energy carriers (electricity, light fuel oil, heavy fuel oil, natural gas, lignite, hard coal, district heating, biomass, etc.).

Information-based policies are generally the most complicated to model due to their rather "qualitative character". The discrete-choice approach, however, allows to consider such qualitative factors. For example, labelling of appliances resulting from the EU Labelling Directive can be modelled by adjusting the logit parameters and thus assuming a less heterogeneous market, in which a higher share of consumers select the appliance with the lowest total cost of ownership. See for example (Elsland *et al.*, 2013).

EU emissions trading can be modelled in the form of a CO_2 price for energy-intensive industries. The detailed technology disaggregation in the industrial sector considering more than 80 individual products and processes allows to consider the scope of the EU ETS on a very detailed level. A combined discrete choice and technology vintage model simulates the change in steam generation technologies as a function of technology parameters, demand, prices and policies.

3.2.4 Key data sets

The main inputs for model calibration like **energy balances, employment, value added** or **energy prices** are calibrated to the most recent EUROSTAT statistics whenever possible. The same holds true for main model drivers like GDP and population. When such data is not available (*e.g.* prices for certain energy carriers) other data (*e.g.* IEA) is used to fill the gaps. The current model version is calibrated on the year 2015.

In the following, an overview of the main sources is provided by model segment for technology-related data not available in EUROSTAT:

Buildings and heating systems: Buildings Performance Institute Europe (BPIE), IEE project TABULA, IEA Building Energy Efficiency Policies (BEEP), IEE project EPISCOPE, ODYSSEE database, country specific research *e.g.* for heat

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pumps.

Appliances residential sector: Ecodesign Directive preparatory studies, ODYSSEE database, market research data from GfK.

Appliances tertiary sector: Ecodesign Directive preparatory studies and additional individual technology studies.

Industrial production: Industry organisations (World steel association, CEPI, Cembureau, Eurochlor, etc.), US geological survey, UNFCCC, UN commodity production database, PRODCOM when possible.

Industry cross-cutting technologies: generated in various technology studies of which many are EU projects (external and in-house).

Industry process technologies: IPPC BREF studies, numerous technology/sectoral studies (external and in-house).

Besides these sources, many more, even country specific sources, statistics and reports are used to feed the model database.

3.2.5 Recent publications using the FORECAST model

Table 12: List of recent projects/studies using the FORECAST model

Project/study	Role of FORECAST	Main objective and results
Industrial Innovation: Pathways to deep decarbonisation of industry Fleiter *et al.*, 2019	Detailed analysis using FORECAST of industrial mitigation pathways considering best available and innovative mitigation technologies for the EU28.	All scenarios show that an ambitious improvement in energy efficiency can reduce the costs of decarbonisation and make substantial contributions to CO_2 savings over the next 10 to 20 years in particular. However, that alone is not enough to reduce emissions sufficiently. A decisive factor is the rapid expansion of renewable energies in order to generate CO_2-free electricity. This is particularly important because electricity consumption in the industrial sector could rise sharply by 2050 - doubling or even tripling depending on the scenario. This would happen above all if electricity were increasingly used for process heat generation and important processes in the chemical and steel industries were converted to electrolysis hydrogen. A 95 percent reduction in greenhouse gases and thus almost CO_2-neutral industrial production by 2050 requires fundamental changes along the value chain. These include the spread of low-CO_2 cement types, efficient use of materials and a comprehensive recycling economy. The capture and storage of CO_2 can also play a role, for example in reducing remaining emissions during the production of cement clinker and lime
REFLEX - Analysis of the European energy system under the aspects of flexibility and technological progress (publication available in 2020) www.reflex-project.eu	Detailed analysis of residential, tertiary, and industrial mitigation pathways in a centralised and decentralised energy system under the consideration of flexibility options (eLOAD) for the EU28.	Electrification and the use of hydrogen are promising decarbonisation options for the demand-side sectors transport and industry. In a decentralised system with volatile renewable energy sources, flexibility potentials play an important role for secure and cost-efficient electricity supply. On the demand-side, the diffusion of decentralised batteries as part of PV systems and in electric vehicles as well as hydrogen production by electrolysers could provide necessary flexibility for the electricity system.

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SET-Nav - Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation Hartner *et al.*, 2019 www.set-nav.eu	The main objective of the simulation of energy in industrial processes has been to set-up a modelling framework that allows simulating the transition to a low-carbon energy system for the industrial sector in an integrated manner. Technology solutions like innovative process technologies, fuel switch to RES, energy efficiency, CCS and the links to the power and gas sectors have been considered using the bottom-up model FORECAST.	The analysis has shown that mitigation levels in industry of more than 80% can only be achieved by either the use of CCS (also for smaller point sources) and/or the implementation of various types of mitigation options including energy-efficient and low-carbon production innovations, RES-based electricity and hydrogen (also as feedstock for the chemical industry), a comprehensive circular economy and improvements in material efficiency. Todays available technologies are insufficient for deep decarbonisation. The remaining energy efficiency potentials due to applying BAT are limited and fuel switching from fossil fuels such as natural gas to RES is often not possible due to the high temperature levels required in industrial furnaces and the competition for biomass with other sectors. In addition, process emissions from chemical reactions within production processes pose a special challenge for the sector as they are difficult or even impossible to mitigate with today's productions processes and products. Consequently, the current policy mix needs to be adjusted in order to effectively support R&D activities directed at the decarbonisation of industrial production.
HotMaps - A unique tool for heating and cooling planning www.hotmaps-project.eu	Development of generic data for specific heating and cooling demand in industry and for technologies in steam generation based on FORECAST. Data collection on heating and cooling demand of energy intensive plants. Data collection regarding the heat supply mix for decentralised heating and cooling systems and district heating and cooling. Development of industrial heat demand and waste heat integration module.	The Energy Efficiency Directive as well as the Rewewable Energy Directive and Energy Performance of Buildings Directive require EU Member States to develop policies foreseeing systematic planning processes for efficient heating and cooling. HotMaps facilitated this task by allowing users to – Map the heating and cooling energy situation including renewable and waste heat potentials in GIS layers in virtually any EU region up to a 250x250m level; – Model the energy system, considering hourly matching of supply and demand, demand response etc. on local, regional and national level; – Simulate supply and demand options of long-term scenarios until 2050 regarding *e.g.* CO_2 emissions, energy costs, demographic changes, share of renewables. – using the developed open source heating and cooling mapping and planning toolbox.
Heat Roadmap Europe – A low-carbon heating and cooling strategy for Europe (HRE4) www.heatroadmap.eu	Modelling of the buildings and industry sectors, and the effect and cost of energy efficiency measures in buildings with FORECAST to generate detailed heating and cooling demand profiles, for the residential, industry and service sector which are used to further calibrate the heating and cooling demands in Pan-European Thermal Atlas and to better understand the possibilities for energy efficiency on the demand side.	Decarbonising heating and cooling requires energy efficiency on both demand and supply sides of the heat sector. Heat savings can cost-effectively reduce the total heat demand in Europe by approximately 30-50%. District heating can capture excess heat, which is currently being wasted, and can replace fossil energy sources to heat EU cities. Based on cost and energy considerations, district heating should increase from today's level of 10% up to 50% by 2050. Large heat pumps and other proven technologies can provide next generation district heating with renewable heat

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3.3 LEAP - Long-range Energy Alternatives Planning System

3.3.1 Short overview

LEAP, the Long-range Energy Alternatives Planning System, is a widely-used scenario-based software tool, which supports a wide range of different modelling methodologies for energy policy analysis and climate change mitigation assessment at many different scales, ranging from cities and states to national, regional and global applications. On the demand side, these applications range from bottom-up end-use accounting techniques to top-down macroeconomic modelling. LEAP's functionalities lay within the core activities of countries undertaking integrated resource planning, greenhouse gas (GHG) mitigation assessments, and Low Emission Development Strategies (LEDS), especially in the developing world. The main purpose of LEAP lies in providing a means of comparison between a "Business as Usual (BaU)" scenario, and other user-customised scenarios promoting the adoption of innovative policies and sustainable strategies in the context of a country, in crucial activity sectors, such as the energy production and the building envelope. LEAP supports numerous scenarios, thus providing for in-depth insights regarding a wide variety of key energy, environmental and socioeconomic indicators. At least 32 countries used LEAP for a variety of tasks focused on the field of GHG mitigation by several techniques, such as changing the energy consumption on the demand side, shifting the energy carrier on the supply side and imposing policies on the supply and demand sides (Martínez-Jaramillo *et al.*, 2017) in the context of creating energy and emissions scenarios, to be the basis for their Intended Nationally Determined Contributions (INDCs) to climate action. (Dagher and Ruble, 2011) constructed LEAP-based scenarios and examined the technical, economic, and environmental implications of all scenarios with regard to electrical planning. Using the LEAP model, Jun and Lee (2010) focused on the penetration of renewable energies on the existing electricity generation market in South Korea, in terms of economic and environmental influence. (Cai *et al.*, 2007) assessed the reduction potential of CO_2 emissions in China's electricity sector and simulated different development paths.

LEAP is based on an integrated, scenario-based structure, which can also be used to track energy consumption, production and resource extraction in all sectors of an economy, including accounting for GHG emission sources and sinks at both the energy and non-energy sectors. LEAP's structure enhances the representation of the energy system of each Member State by breaking down the energy used in each economic activity, even to the "lowest" level (*i.e.* households). It also allows for the modelling of several energy production units (*e.g.* lignite, natural gas, renewables, etc.) along with their technical specifications (*e.g.* power, technical minimum, lifetime, fuel, etc.) as well as optimised unit commitment, in terms of meeting the end-user demand curve with the minimum cost. Energy CO_2 emissions and other greenhouse gases (*e.g.* CO_2 from others sources, CH_4, N_2O, HFCs, PFCs and SF_6) are then calculated by the model, with respect to the energy production side. In addition to tracking GHG emissions, LEAP can also be used to analyse emissions of local and regional air pollutants, and short-lived climate forcers (SLCFs), making it well-suited to studies of the climate co-benefits of local air pollution reduction. Given LEAP's diversity, it can be used to explore GHG mitigation alternatives through energy system transformations as well as to provide policy insights towards transitioning to a climate-resilient energy sector.

3.3.2 Key features of the LEAP tool

3.3.2.1 Energy sectoral detail

On the demand side, each sector is modelled as a production or an energy intensity level and the use of other key intermediate factors (capital, intermediate consumptions, etc.) given its expectations on demands and prices. Regarding the end-user side specifically, the final demand is usually broken down into four major categories: a) residential, b) agricultural, c) commercial and d) transport, providing the user with the capacity to introduce all

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associated information, such as (non-) electrified households, passenger- and ton-km, etc. As we move further from the demand side, LEAP allows the user to model the energy production side, along with their respective networks and implications (e.g. resource limitations and energy losses). This approach can be used to fully describe individual policy measures which can then be combined in different combinations and permutations into alternative integrated scenarios, thus allowing policy makers to assess the impact of an individual policy as well as the interactions that occur when multiple policies and measures are combined, in terms of both energy and environmental impact.

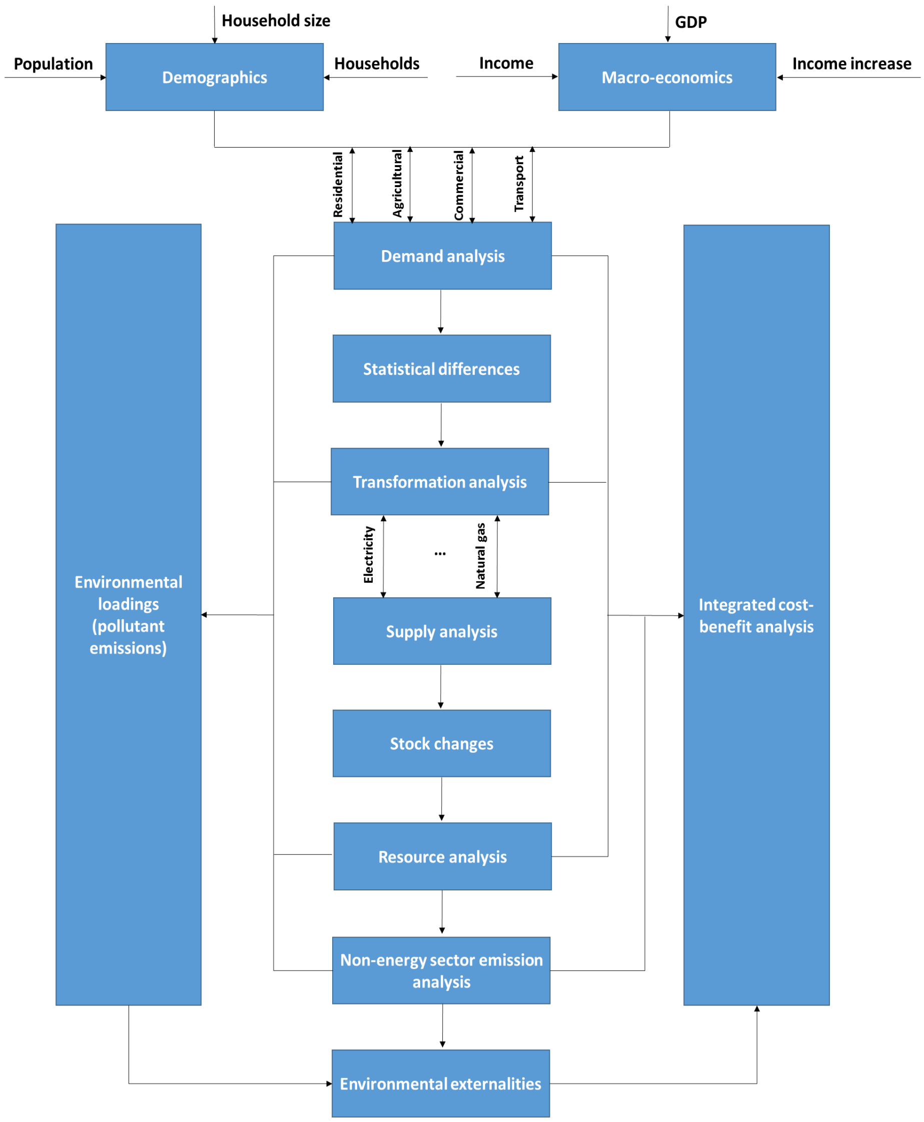

Figure 6: Representation of the LEAP energy system

Source: LEAP User Guide, 2005; own elaboration

3.3.2.2 Geographic coverage

LEAP provides a range of accounting, simulation and optimisation methodologies that are powerful enough to easily incorporate data and results from other more specialised models, thus making LEAP an integrated tool spanning across the entire globe, at national, regional and local level (Table 13).

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Table 13: Regional representation and countries included in each region in LEAP

Geographic region	Countries
Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe, and Other Africa
Australia, New Zealand	Australia, New Zealand
Canada	Canada
North America	US, Mexico
Latin America	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and Other Latin America
Central and Eastern Europe	Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Serbia and Montenegro, Slovenia, Slovakia
Middle East	Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen, and Turkey, Cyprus
Russia and Central Asia	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Russian Federation
(Other) South and Southeast Asia	Bangladesh, India, Brunei Darussalam, Cambodia, Taiwan (China), Indonesia, DPR of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam and Other Asia (Japan, China, Republic of Korea, etc.)
Western Europe	Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Norway, Portugal, Spain, Sweden, Switzerland, The Netherlands, UK

3.3.2.3 Multi-year time periods

LEAP is intended as a medium- to long-term modelling tool. Its calculations occur based on a user-defined time-step (*e.g.* annual, 5-year period, etc.) and baseline year (*e.g.* 2005, 2010, etc.), and the time horizon can extend to an unlimited number of years (beyond 2100). Studies typically include both a historical period known as the Current Accounts, in which the model is run to test its ability to replicate known statistical data, as well as multiple forward-looking scenarios. Typically, most studies use a forecast period of between 20 and 50 years.

3.3.2.4 Intra-year time periods (time slices)

Some results are calculated with a finer level of temporal detail. For example, the year can be split into different user-defined "time slices" to represent seasons, types of days or even representative times of the day. These slices can be used to examine how loads vary within the year and how electric power plants are dispatched differently in different seasons. LEAP includes an easily-customised dataset of time-slices, which extends from seasonal segregation (*i.e.* summer, winter, autumn, fall) today- and night- time of all seasons as well as hourly representation. This kind of in-depth time-slicing seeks to provide analytical insights and partially offset the stochastic nature of the energy production sector (given the high RES penetration) and the fluctuating end-user demand across the year, by facilitating the matching of supply and demand in each time-slice.

3.3.3 Climate module & emissions granularity

The climate component in LEAP includes a diverse database of both energy and non-energy sector GHG emissions per fuel or activity, thus calculating the final GHG emissions stemming from an energy system's operation at global, national, regional, or local level, based on the initial energy and socioeconomic data provided (*e.g.* demographics, income, GDP, etc.). The tool tracks far beyond the three main sources of greenhouse gases (*i.e.* CO_2, CH_4, and N_2O),

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extending its analysis to tracking SLCFs such as fluorinated gases, black carbon, etc. The LEAP model also includes the Technology and Environmental Database (TED), which provides extensive information describing the technical characteristics, costs and environmental impacts of a wide range of energy technologies (including existing technologies, current best practices and next generation devices), compiled from numerous sources (*e.g.* Eurostat, EEA, etc.). Thus, LEAP is appropriate for energy policy analysis and climate change mitigation assessment. Since LEAP is a scenario-based modelling tool, its climate module calculates changes in the atmospheric concentration of all implicated GHG emissions between a reference scenario (which depicts the current condition of a system in terms of energy—demand and supply—and demographics—population, income, etc.) and a number of GHG mitigation-oriented scenarios based on current and future limitations, aligned with the ongoing global treaties and agreements (such as the goals set by the Paris Agreement or by increasing ambition).

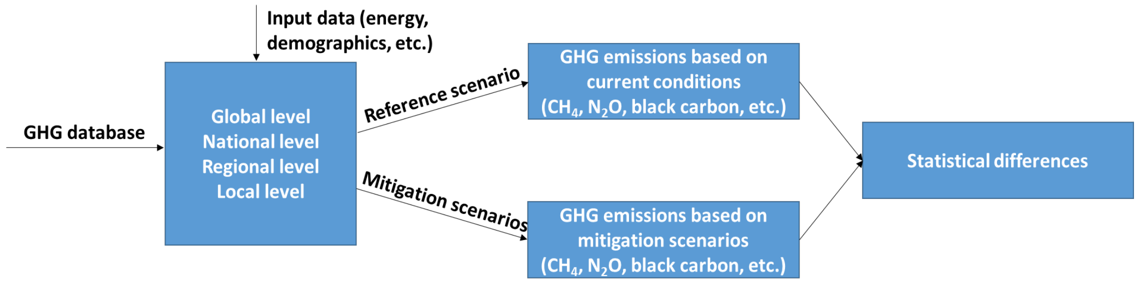

Figure 7: Logic of LEAP climate module

Source: LEAP User Guide, 2005; own elaboration

3.3.4 Socioeconomic dimensions

LEAP requires in-depth inputs regarding the changes in socioeconomic conditions (*e.g.* population, household size, etc.) and energy sector (*e.g.* supply and demand), as well as demand for other goods and services that affect GHG emissions (such as agricultural demand) for both the reference and the mitigation scenarios, over the time horizon of the analysis. It should be noted that LEAP does not include a default set of socioeconomic and energy data, since it is an easily-customised tool that can be adjusted to use several socioeconomic and sectoral growth projections from different sources (aside from SSPs). Since the economic, population and sectoral growths are used to capture specific drivers for the changes in energy demand in a reference scenario (in which no climate change mitigation measure has been applied), LEAP allows users to self-assess and define the sets of energy service demands over the horizon, as well as to quantify them based on a diverse set of quantification units. This set of quantification varies from passenger-kms and tonne-kms in the transport sector to kWhs and metric tonnes in the industrial sector, as well as to Gigajoules of final consumption per unit of activity level (GJ/€). LEAP is also widely open to conducting cost-benefit analyses if the required socioeconomic and energy inputs needed are partially available.

3.3.5 Calibration of the model

LEAP is calibrated for the initial period, in terms of fuels, based on a standard fuels database drawing data from IEA, UN and other standard international sources (such as the IPCC). These data sources should suffice for most LEAP analyses. However, LEAP allows the user to edit the default data, for example to change the energy contents of certain fuels (such as coal and wood) to reflect the conditions in the area they aim to study. In addition, LEAP provides an "Add" and "Delete" button for the user to add a new fuel and delete one respectively, if necessary, and manually define its respective specifications. Regarding the projections for energy in the reference and

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mitigation scenarios, the installed technological capacity along with its CAPEX and OPEX, the exported, imported, produced and consumed quantities for all energy carriers etc., LEAP does not include a respective database, and therefore this kind of data must be entered and updated manually.

3.3.6 Mitigation/adaptation measures and technologies

LEAP includes a wide dataset of the most major fossil fuel and low-carbon technologies that are perceived to be commonly exploited in the upcoming years. Thus, for each economic activity, the energy demand is broken down in key categories such as oil, gas, solid fuel, biomass, etc. Regarding the electricity sector, LEAP allows for an in-depth representation of the energy mix capability by providing several energy-based production units such as, solar, nuclear, wind, etc. By simulating the substitution of low-carbon for high-carbon technologies in response to their relative costs, as well as emissions constraints, the LEAP model simulates mitigation. The principal energy sector CO_2 mitigation technology options are as shown in Table 14. The plethora of energy choices that LEAP provides can be crucial for the suggestion of several mitigation/adaptation policies. These scenarios may aim to the reduction of GHG emissions or the abatement of the cost of energy production. An interesting example is the choice between hydroelectric power and nuclear power. Both energy sources are emission-free but each of them features different costs depending on the region they are applied.

Table 14: Main CO_2 energy system mitigation options in LEAP

Electricity and heat	
Electricity generation	***Heat generation***
Nuclear fission Nuclear fusion Hydro Biomass Geothermal Solar PV Solar CSP Onshore wind Offshore wind	Geothermal Biomass
Transport	
Road	***Rail***
Gas (LNG / CNG) vehicles Fully electric vehicles Biofuels in fuel mix Efficiency	Electric Efficiency
Air	***Marine***
Biofuels in fuel mix Electric planes Efficiency	Gas Biofuels Electric Efficiency
Buildings	
Heating	***Lighting***
Gas replacing coal / oil Biofuels Electricity Solar thermal Efficiency	Efficiency
Appliances	***Cooling***
Efficiency	Electricity Efficiency
Industry	
Process heat	***Steam***
Gas replacing oil / coal Biomass Electricity	Gas replacing oil / coal Electricity
CHP	
Gas replacing oil / coal Biomass	
Agriculture	
Energy use	
Gas replacing oil/coal Biomass Electricity	

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3.3.7 Economic rationale and model solution

LEAP simultaneously calculates the quantity of the energy produced, converted and consumed with regard to the different "commodities" accounted for in the model, the total GHG emissions stemming from a system's operation, as well as the way in which these emissions are broken down into each sector, in a given region or economy under a range of alternative assumptions on population, economic development, technology, prices and so on. These commodities comprise the different energy forms, the deployed technologies, and the energy services. LEAP allows to reach a cost-minimising level of commodity production and consumption, consistent with meeting all current and future energy demands and emissions constraints. The total energy system cost is calculated as a Net Present Value (NPV) cost of the energy system over the entire pre-defined time horizon. With its flexible data structures, LEAP allows for analysis as rich—in technological specification and end-use detail—as the user chooses. All of the aforementioned features contribute to the creation and evaluation of multiple alternative mitigation scenarios. These scenarios can be compared with a reference scenario (which projects the progress of energy demand, energy production, social costs and GHGs emissions of the region studied if no significant changes occur on the current energy system), in order to evaluate the contingent reduction of GHG emissions or social costs of the different mitigation scenarios suggested.

3.3.8 Policy questions and SDGs

3.3.8.1 Key policies that can be addressed

LEAP can be used to project the energy supply and demand situation in order to get a glimpse of future patterns, identify potential problems, and assess the likely impacts of energy policies. In this respect, LEAP allows to examine a wide variety of projects, programs, technologies and other energy initiatives, and arrive at strategies that best address environmental and energy problems. Some indicative policies that can be implemented in LEAP are the following:

- Minimum/maximum capacity factors on fossil fuel power generation plants (*e.g.* to simulate minimum or maximum desired levels of operation);
- Constraints on the CO2-related primary energy resources exploited (*e.g.* limit the availability of fossil fuels down to its minimum in the upcoming years);
- Energy consumption cuts through increasing energy efficiency on the end-users' side (*e.g.* withdrawal of an outdated car fleet and replacement with new vehicles, based on cleaner fuels with lower consumption, such as CNG);
- Subsidies on particular technologies (through adjusting their costs);
- Constraints on the availability of particular technologies (*e.g.* "no nuclear");
- Constraints on the growth rates of particular technologies (*e.g.* natural gas units and substitution with renewable energy sources);
- Constraints on the growth rates of particular socioeconomic aspects (*e.g.* population, income, GDP, etc.);

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

- What impact will current efforts towards expanding clean energy resources have over time and which policies are the most effective, in terms of both minimising costs and maximising social benefits?
  - For example, Abt Associates (2017) explore the costs and benefits stemming from the implementation of different mitigation options both in the energy and transport sectors of Azerbaijan, Kazakhstan, and Uzbekistan, in terms of GHG abatement and social benefits. The effectiveness of these options was assessed in terms of GHG abatement, and social benefits.
- Where can we do more to promote a green future?
  - For example, Ouedraogo (2017) and Emodi *et al.*, (2017) showcase the mitigation potential in

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different activity sectors in Africa (through the analysis of several mitigation scenarios), and their close association with socioeconomic variables such as gross domestic product, income per capita.

- What amount of clean energy is needed to adequately reduce carbon pollution and meet current emissions targets?
    - For example, Mirjat *et al.*, (2015) explore the energy supply mix that needs to be produced in order to meet Pakistan's final energy demand, in alignment with the national and global GHG emissions reduction target.

3.3.8.2 Implications on other SDGs

LEAP does not automatically calculate the implications on non-climate SDGs of its least-cost energy system to meet prescribed climate or emissions constraints. However, it is possible to exploit LEAP's outputs and conduct "off-model" calculations to estimate many of the SDG implications. For example, LEAP reports the total final energy consumption in an energy system. This energy can be reshaped at lower/higher levels, depending on the successful implementation of different mitigation scenarios, thus allowing for an estimation of the energy-poor citizens.

3.3.9 Recent publications using the LEAP model

Table 15: List of recent publications using the LEAP model

Paper	Topic	Key findings
Mirjat et al., (2015)	Long-Term Electricity Demand Forecast and Supply Side Scenarios for Pakistan (2015-2050): A LEAP Model Application for Policy Analysis.	Given that the balance between demand and supply of electricity in Pakistan is yet to be achieved, in this study, Long-range Energy Alternatives Planning System (LEAP) is used to develop Pakistan's LEAP modelling framework for the period 2015–2050, through four supply side scenarios, following the demand forecast. In the most effective scenario (Energy Efficiency and Conservation) there is a CO_2 reduction higher than 50% on the in 2050.
Emodi et al., (2017)	Energy policy for low carbon development in Nigeria: A LEAP model application.	This paper applied a scenario-based analysis to explore Nigeria's future energy demand, supply and associated GHG emissions from 2010 to 2040 through the analysis of a reference scenario, a low-carbon moderate scenario, a low-carbon advanced scenario, and a green optimistic scenario. It is observed that in the Green Optimistic scenario the emissions will be 11% lower than in the reference scenario.
Martínez-Jaramillo et al., (2017)	Assessing the impacts of transport policies through energy system simulation: The case of the Medellin Metropolitan Area, Colombia.	This paper quantifies the emissions that could be avoided by the implementation of Medellin's Master Plan, the promotion of telecommuting, and the development of a transport energy model for the Medellin metropolitan area between 2010 and 2040. The results indicate that a policy combining the promotion of mass transportation could represent 5.65 Million Tons of CO_2 equivalent avoided by 2040 (a 9.4% reduction).
Abt Associates (2017)	Economics of Climate Change in Central and West Asia.	LEAP was used as the main modelling tool for analysing the costs and benefits of mitigation options in the energy and transport sectors of Azerbaijan, Kazakhstan, and Uzbekistan. The effectiveness of the examined options was assessed in terms of GHG abatement, and net social costs and benefits.
Ouedraogo (2017)	Energy futures modelling for African countries.	An assessment of the current and future trends in energy demand in Africa and associated GHG emissions. Future energy demand is forecasted on the basis of socioeconomic variables such as gross domestic product,

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		income per capita, population, and urbanisation. LEAP is applied to analyse and project energy demand and the related emissions under alternative strategies for the period 2010–2040.
Huang *et al.*, (2011)	The long-term forecast of Taiwan's energy supply and demand: LEAP model application.	The Taiwan LEAP model is used to compare future energy demand and supply patterns, as well as greenhouse gas emissions, for several alternative scenarios of energy policy and energy sector evolution. An interesting conclusion of this study is the fact that if the existent nuclear plants are retired but not replaced by RES, there will be a higher demand for coal and other fossil fuels, which will result in the increase of greenhouse gases emissions.

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3.4 JET - JRC-EU-TIMES

3.4.1 Short overview

TIMES is a modelling platform for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating how energy system operations will evolve over a long term, multiple period time horizon (Loulou and Labriet, 2008) These energy system operations include the extraction of primary energy such as fossil fuels, the conversion of this primary energy into useful forms (such as electricity, hydrogen, solid heating fuels and liquid transport fuels), and the use of these fuels in a range of energy service applications (vehicular transport, building heating and cooling, and the powering of industrial manufacturing plants). In multi-region versions of the model, the trade of fuels between regions is also estimated. The TIMES framework is usually applied to the analysis of the entire energy sector, but it may also be applied to the detailed study of single sectors (*e.g.* the electricity and district heat sector).

The JRC-EU-TIMES (JET) model, is the multi-region, European version of TIMES, which is designed for analysing the role of energy technologies and their innovation needs for meeting European policy targets related to energy and climate change. It models technologies uptake and deployment and their interaction with the energy infrastructure in an energy systems perspective. It is a relevant tool to support impact assessment studies in the energy policy field that require quantitative modelling at an energy system level with a high technology detail. The JRC-EU-TIMES model represents the EU Member States and neighbouring countries, where each country is modelled as one region; producing projections (or scenarios) of the EU energy system showing its evolution up to 2060 under different sets of specific technology and policy assumptions and constraints.

JRC-EU-TIMES is an improved offspring of previous European energy system models developed under several EU funded projects, such as NEEDS[6], RES2020[7], REALISEGRID[8], REACCESS[9] and COMET[10]. The JRC-EU-TIMES model has been further developed over the last years by JRC unit C.7[11].

3.4.2 Key features of the JET model

3.4.2.1 Energy sectoral detail

The JRC-EU-TIMES model considers both the supply and demand sides and includes the following seven sectors: primary energy supply (including transformation); electricity generation; industry; residential; commercial; agriculture; and transport.

The most relevant model outputs are the annual stock and activity of energy supply and demand technologies for each region and period. This is accompanied by associated energy and material flows including emissions to air and fuel consumption, detailed for each energy carrier. Besides technical outputs, the associated operation and maintenance costs, the investment costs for new technologies, all energy and materials commodities prices (including for emissions if an emission cap is considered), are obtained for every time step.

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6 "NEEDS project," [Online]. Available: http://www.needs-project.org.
7 "RES 2020 project," [Online]. Available: http://www.cres.gr/res2020.
8 "REALISEGRID project," [Online]. Available: http://realisegrid.rse-web.it
9 "REACCESS project," [Online]. Available: http://reaccess.epu.ntua.gr
10 "COMET project," [Online]. Available: http://comet.lneg.pt
11 A list of publication is available online at: https://ec.europa.eu/jrc/en/publications-list/%2522jrc-eu-times%2522

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A simplified overview of the JET energy sectors structure is shown in Figure 8.

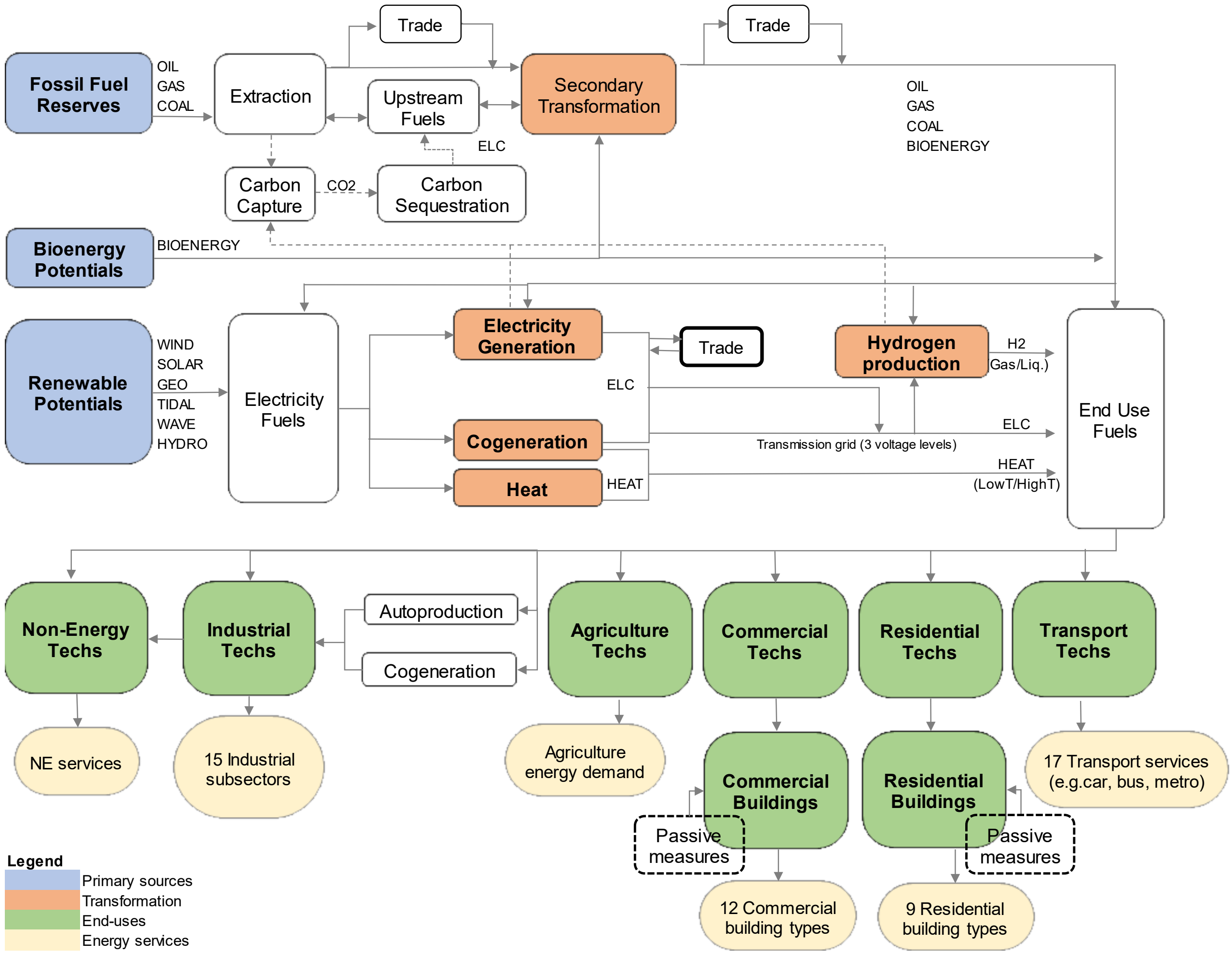

Figure 8: Representation of the JET energy system for each region

Source: Own elaboration

3.4.2.2 Geographic coverage

The JRC-EU-TIMES includes in its base version 31 regions, connected by energy/emissions trade, as follows: the EU-28 (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Hungary, Ireland, Italy, Lithuania, Luxemburg, Latvia, Malta, the Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia and the United Kingdom) and Non-EU countries (Switzerland, Iceland, Norway). The model can be optionally further expanded to the Balkans regions (Albania, Bosnia and Herzegovina, Kosovo, The Former Yugoslav Republic of Macedonia, Montenegro, and Serbia), although this configuration requires some modelling work.

Each country is represented as one single region, as shown in Figure 9.

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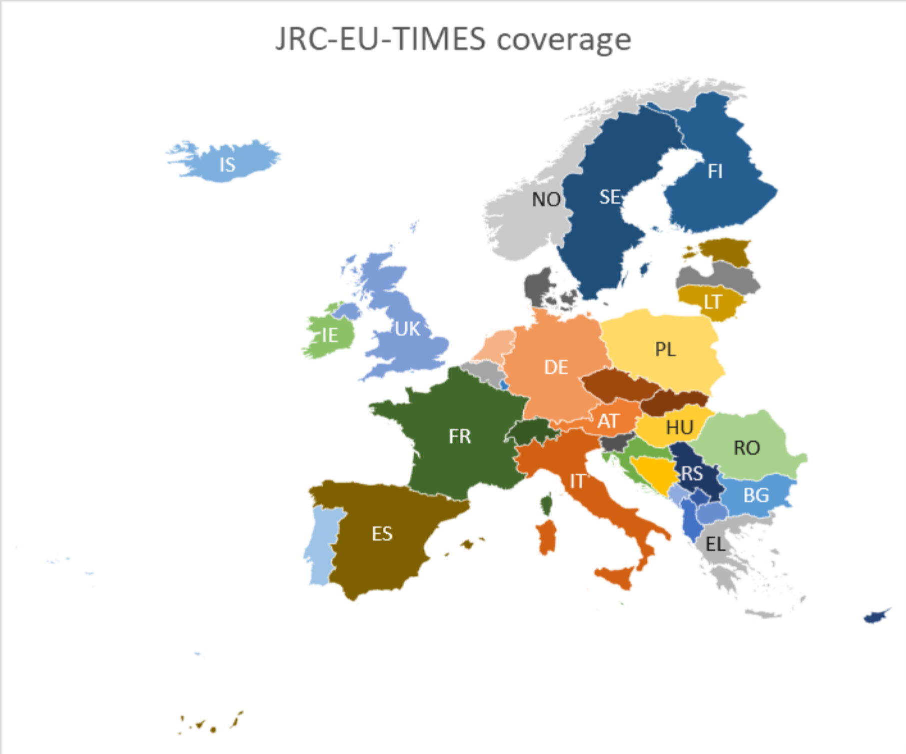

Figure 9: Regional representation and countries in the JET model

Source: Own elaboration

3.4.2.3 Multi-year time periods

According to its analytical paradigm, JRC-EU-TIMES models energy dynamics over a multi period time horizon. The time horizon over which the model simulates the evolution of the energy system is divided into a user-chosen number of time-periods; which can vary depending on a number of factors, such as the scope of the analysis, model setup, computational limitations, etc.

In its current version, the JRC-EU-TIMES model runs from 2010 (base year) until 2060, with flexible number of intervals (from four to twelve). 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, model can run different horizons/organisation of periods (if needed/helpful).

3.4.2.4 Intra-year time periods (time slices)

In addition to the multi-year time periods described above, in the JET there are time divisions within a year, called "time slices", which may be defined by the user, so as to capture different weather conditions, consumer behaviours, and energy demand conditions at different times of the year. There are currently twelve time-slices representing an average of day, night and peak demand for every one of the four seasons of the year (*e.g.* summer day, summer night and summer peak, etc.).

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, 2008). 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

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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.

3.4.3 Emissions granularity

The model tracks the main source of greenhouse gases in the energy sector, *i.e.* carbon dioxide (CO_2) from both combustion and industrial processing. A special module of the JET can be enabled to allow emissions trading across the model regions.

3.4.4 Socioeconomic dimensions

The JRC-EU-TIMES model requires inputs concerning the degree to which energy demands, as well as demand for goods and services that result in GHG emissions, will grow over the course of the next decades in the different countries.

Key drivers to the JRC-EU-TIMES model are the socioeconomic projections of GDP growth; private consumption as a proxy for disposable income; price evolution and sector production growth, population and number of households etc.; for each country in the model. These drivers are transformed into the different final annual end-use demand projections, which are the key quantities that the JRC-EU-TIMES model must produce an energy system to satisfy. The building-related sectors (namely residential and commercial sectors) require a more detailed approach, as to generate the demands for heat, cooling and hot water, characteristics of dwellings are explicitly represented (Chiodi *et al.*, 2017).

Across the years several sources and methodologies have been employed to generate updated JRC-EU-TIMES energy services demands. For example in Simoes *et al.* (2017), the materials and energy demand projections for each country are differentiated by economic sector and end-use energy service, using as a starting point historical 2005 data and macroeconomic projections from the GEM-E3 model (Russ *et al.*, 2009) as detailed in (Simoes *et al.*, 2013), and in line with the values considered in the EU Energy Roadmap 2050 reference scenario (EC, 2011). These projections have been further updated to align with latest socioeconomic projections in use within the European Commission (Nijs *et al.*, 2019; Nijs *et al.*, 2017).

3.4.4.1 Energy demand drivers and demand elasticities

In total, the JRC-EU-TIMES represents about 60 different types of energy services for the transport, residential, agricultural, commercial, industry and non-energy sectors. Some examples include number of residential and commercial dwelling stocks (thousands of dwellings), public street lighting (thousands of lighting points), industry iron & steel (millions of tonnes), transport car distance (billions of passenger kilometres) and transport road freight (billions of tonne kilometres).

The socioeconomic, population and physical drivers (*e.g.* physical production of industrial activities, expected numbers of new dwellings) are used as specific drivers for the growth in energy demands, associated when relevant to *demand elasticities*, see Loulou *et al.* (2016) for more details.

Once the drivers for the different energy demands represented by JRC-EU-TIMES model are selected, allocated and quantified, the construction of the reference demand scenario requires computing a set of energy service demands over the horizon.

Furthermore JRC-EU-TIMES has the capability of estimating the price-based response of these energy service demands to the changing conditions of scenarios in which mitigation occurs. For example, if the cost of energy increases as fossil fuels are replaced by renewables, then the demand for energy services would decrease. To do

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this, JRC-EU-TIMES makes use of another set of inputs, namely *own price elasticities*, applied to each model energy service. This option can be easily disabled, assuming in that case energy service demands to be inelastic.

3.4.5 Calibration of the model

The JRC-EU-TIMES model is calibrated to the year 2010 (base-year) and key commodity variables aligned with statistics in the period 2011-2014. The calibration makes use of a combination of the latest available information and statistics about the EU energy sectors, namely: energy balances from Eurostat and IEA (only for regions currently not covered by Eurostat), and detailed databases such JRC-IDEES[12], TRACCS[13] and ENTRANZE[14].

3.4.6 Mitigation/adaptation measures and technologies

JRC-EU-TIMES 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 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 typical question that JRC-EU-TIMES can address is what technologies are competitive under various policy scenarios. For emerging technologies with a small uptake, JRC-EU-TIMES can estimate what technology improvements would be needed to make these competitive (Nijs *et al.*, 2018).

The principal energy sector mitigation options are shown in Table 16, where the options that can be potentially added 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.

Moreover the JRC-EU-TIMES might be set to simulate impacts of a number of adaptation measures, as listed in Table 17; such restrictions in water availability, changes in building envelope requirements, or increased requirements for specific energy services.

[12] https://ec.europa.eu/jrc/en/potencia/jrc-idees
[13] https://traccs.emisia.com/
[14] https://www.entranze.eu/

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Table 16: Main GHG energy system mitigation options in JRC-EU-TIMES

Upstream	
Synthetic fuel production	***Hydrogen production***
Coal to gas without CCS Coal to liquids without CCS Biomass to gas without CCS Biomass to liquids without CCS Coal to gas with CCS* Coal to liquids with CCS* Gas to liquids with CCS* Biomass to liquids with 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 Nuclear 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 (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 oil / coal Biofuels Electricity Hydrogen Solar thermal Building shell efficiency (Roof insulation, Wall insulation, Windows replacement)	Efficiency
Appliances	***Cooling***
Efficiency	Electricity
Behaviour change	***Other***
Demand response to price signals Behaviour change in buildings	Energy poverty (proxy)
Industry	
Process heat	***Machine drives***
Gas replacing oil / coal Biomass Hydrogen Electricity	Gas replacing oil / coal Electricity
Steam	***CHP***
Gas replacing oil / coal Electricity	Gas replacing oil / coal Biomass
CCS	***Other***
CCS in iron and steel CCS in cement	Demand response to price signals

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CCS in pulp & paper CCS in non-metallic minerals CCS in chemicals	
Agriculture	
Energy	***Other***
	Demand response to price signals

**: option that can be potential added*

Table 17: Main adaptation measures in JRC-EU-TIMES

Water	*Heating & Cooling*
Water use restrictions	Additional cooling of buildings Building material choices

3.4.7 Economic rationale and model solution

According to its analytical paradigm, the JRC-EU-TIMES 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 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 most relevant model outputs are the annual stock and activity of energy supply and demand technologies for each region and period. This is accompanied by associated energy and material flows including emissions to air and fuel consumption, detailed for each energy carrier. Besides technical outputs, the associated operation and maintenance costs, the investment costs for new technologies, all energy and materials commodities prices (including for emissions if an emission cap is considered), are obtained for every time step.

JRC-EU-TIMES combines a social approach towards the time value of money and a private approach towards risk as well as the cost of financing based on the individual technologies. The JRC-EU-TIMES model uses a mix of private and social discount rates, since for the evaluation of investment decisions private discount rates are used, but for the timing of investment a social discount rate is applied. The first determines whether an investment pays off with the assumed private discount rate. The higher the (perceived) risk is, the higher the discount rate. Technologically specific discount rates are used to balance planning approaches and include risks for specific technologies. The second determines when is the best timing to do investments reflecting the time preference for consuming as well as a decreasing marginal utility of future consumption. This discount rate is applied primarily to make intertemporal decisions based on Net Present Value (Nijs *et al.*, 2019).

3.4.8 Value of key parameters

The JRC-EU-TIMES 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.

In line with this concept JRC-EU-TIMES monitors cost evolution of a large subset of technologies from the upstream (*e.g.* costs of primary resources), transformation (*e.g.* electricity and hydrogen production), and final consumption (*e.g.* end-use sectors technologies; as appliances, cars, etc.).

Given the European context and its central focus on boosting decarbonisation, renewables and energy efficiency;

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the model, since its origins, had a specific focus on low carbon technologies, in particular the one identified by the EU SET Plan (Strategic Energy Technology Plan)[15]. Most recent model updates and analyses on technology have focused on improving knowledge on hydrogen and power to liquid technologies (Blanco *et al.*, 2018; Kanellopoulos *et al.*, 2019 and Sgobbi *et al.*, 2016), Heating & Cooling (Chiodi *et al.*, 2017 and Nijs *et al.*, 2017), electromobility (Thiel *et al.*, 2016), retrofit measures in buildings (Chiodi *et al.*, 2017), electricity storage (Nijs *et al.*, 2014) and other key low carbon technologies (Nijs *et al.*, 2018) and (Simoes *et al.*, 2017)). Datasets with renewable energy potentials (Ruiz *et al.*, 2015 and Ruiz Castello *et al.*, 2019) have also been made publicly available.

In the framework of the *Paris Reinforce* project, the following key information can be considered as the parameters to monitor, discuss and evaluate as to guarantee a successful integration with the other tools and analyses:

- Renewable energy and CCS costs/potentials.
- Quantities and/or prices of trade for main energy commodities.
- Under construction/planned/possible energy projects/infrastructures.
- Burden/contribution of Member States to the EU Energy Union objectives and other specific policies.
- Technology costs and characteristics, in particular for key end-use sectors.

Cost and policy parameters can be revised and updated, following the feedback of national experts (stakeholder engagement), the comparative assessment with other modelling experiences, and the discussion with the partners (modellers).

3.4.9 Policy questions and SDGs

3.4.9.1 Key policies that can be addressed

As for all TIMES-based models, JRC-EU-TIMES can consider policies that affect either the entire energy system, sectors, group of technologies/commodities, or single technologies/commodities. For example, the following policies can be implemented:

- Carbon emissions constraint or a carbon price (imposed as a tax) in each region that it represents, or alternatively all regions simultaneously.
- Subsidies/capital grants on specific sets technologies (*e.g.* on solar PV).
- 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 (such as the EU Emissions Trading System - EU ETS).
- Technology standards (*e.g.* efficiency labelling or ban of specific technologies).

For JRC-EU-TIMES the most commonly applied policies include:

- Feed-in Tariffs and green certificates on renewable technologies.
- Renewable targets in gross final energy consumption (e.g. in line with EU Renewable Energy Directive RED).
- Emission targets (*e.g.* the EU Effort Sharing Regulation - ESR).

Furthermore, the structure of the JRC-EU-TIMES may allow (although some modelling expansion is required[16]) the

[15] https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan
[16] There is the option to hard-link the JRC-EU-TIMES model with the global model ETSAP-TIAM, as to explicitly represent energy dynamics for both world macro-regions and European countries. One of the strengths of this set up is that it

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exploration of energy security concepts, with the possible analysis of scenario variants and policies related to criticalities across sensitive corridor hubs (*i.e.* EU REACCESS project[17]), and security of supply (Chiodi *et al.*, 2016).

Table 18 below provides additional information about the capability of the model to represent policies and measures across the five key energy and climate dimensions, as defined by the governance of the EU energy union.

Table 18: Capability of the JRC-EU-TIMES to address policy and measures

PaMs (by dimension)[18]	JRC-EU-TIMES
Decarbonisation	***High*** capability (several mitigation options, regulatory and economic measures, etc.)
Energy Efficiency	***High*** capability (several energy efficiency options, regulatory and economic measures, etc.)
Energy Security	***Medium/High*** capability (key focus of the previous European project REACCESS, which used the JET in conjunction with ETSAP-TIAM model)
Internal energy markets	***Medium*** capability (electrification, hydrogenation, power-to-gas/liquid, interconnectivity, etc.)
Research, Innovation and competitiveness	***Low-Medium*** capability (implicit and/or *ex-post*)

3.4.9.2 Implications for other SDGs

Apart from the above-mentioned dimensions, a number of Sustainable Development Goals (SDGs) can be taken into consideration and investigated making use of the JRC-EU-TIMES model, as shown below.

Table 19: Capability of the JRC-EU-TIMES consider/assess other SDGs

SDGs	JRC-EU-TIMES
§7. Affordable and clean energy (*e.g.*, traditional biomass use, %renewable energy)	***Full***. Full assessment of cost-effectiveness of RES within a specific storyline.
§8. Decent work & economic growth (*e.g.*, impact on GDPpc, jobs)	***Partial (requires further developments)***. The implementation of an optional TIMES plugin (currently not implemented), the macro module, may allow the estimation of GDP losses due to delivery of Paris Agreement climate targets.
§9. Industry, innovation & infrastructure (*e.g.*, R&D investments)	***Partial***. Limited to the quantification of the energy-related system costs and investment needs required to deliver energy and climate policies.
§11: Sustainable Cities & Communities (*e.g.*, PMs from city transport and buildings)	***Limited***. Although JRC-EU-TIMES does not have a geographical representation of cities and communities (*i.e.* each region is represented as a single node), It explicitly represents the building stock by building type (*i.e.* detached, semidetached and flat), by country (*i.e.* 37 countries) and by construction period (*i.e.* six

describes global dynamics on the basis of a new detailed representation of the European context, expanding the scope of scenario analysis.

[17] "REACCESS project," [Online]. Available: http://reaccess.epu.ntua.gr

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

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	periods). These outputs might inform more detailed out-of-model analyses on Sustainable Cities & Communities
§12: Responsible production & consumption (*e.g.*, % recycled waste, embedded emissions)	***Limited***. Limited to energy (and water) uses and production.
§15: Life on land (*e.g.*, land use for forests, rate of land use change)	***Limited/Simplified***. Afforestation measures can be considered; RES potential/exploitation and investment decisions (*e.g.* energy infrastructures) can be subject to land-specific constraints (natural and regulatory).

3.4.10 Recent publications using the JRC-EU-TIMES model

Table 20: Recent publications using the JRC-EU-TIMES model

Paper	Topic	Key findings
Kanellopoulos *et al.*, 2019	The potential role of H_2 production in a sustainable future power system	The operation of a future highly decarbonised (95% CO_2 emissions reduction vs 1990) power system, as defined with JRC-EU-TIMES in 2050, is analysed with the METIS model. Under the assumption of adequate competition between the electrolyser operators the resulting prices could, in most EU Member States, arrive at a sustainable equilibrium.
Nijs *et al.*, 2019	Deployment scenarios for low carbon energy technologies	This report provides an outlook for deployment of a set of low carbon energy technologies, as well as background on how JRC-EU-TIMES baseline and decarbonisation scenarios are derived. The analysis shows the different role of technologies – such nuclear, CCS, hydrogen, wind, solar, ocean energy, geothermal, etc. – under two key underpinning scenarios: *i*) a world where Member States uses all technology options to decarbonise (including CCS and nuclear), and *ii*) a pro renewables world, where decarbonisation is mainly driven by renewable resources.
Paardekooper, *et al.*, 2018	Heat Roadmap Europe. Quantifying the Impact of Low-carbon Heating and Cooling Roadmaps	The Heat Roadmap Europe provides scientific evidence required to effectively support the decarbonisation of the heating and cooling sector in Europe and democratise the debate about the sector. The report indicates that the EU should focus on implementing change and enabling markets for existing technologies and infrastructures in order to take advantage of the benefits of energy efficiency in a broader sense and for the heating and cooling sector specifically.
Simoes *et al.*, 2017	Comparing policy routes for low-carbon power technology deployment in EU – an energy system analysis	The JRC-EU-TIMES model is used to support energy technology R&D design by analysing power technologies deployment till 2050 to different decarbonisation exogenous policy routes. Paper concludes that R&D can be tailored to depending on how sensitive technologies are to the policy routes. R&D priority should be given to those technologies that are in any case deployed rapidly across the modelled time horizon (as PV) as this could significantly reduce the energy system costs, but also to those that are deployed up to their maximum technical potentials and that are typically less sensitive to exogenous policy routes (as hydro and geothermal). For these 'no regret' technologies, R&D efforts could be mainly directed to increase their technical potential for implementation. For yet 'sensitive' to exogenous

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		policy routes technologies (as CSP and marine), efforts should be assigned to improving their techno-economic characteristics such as capacity factors or associated costs.
Sgobbi *et al.*, 2016	How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system	The JRC-EU-TIMES model is used to assess the role of hydrogen in a future decarbonised Europe under key climate scenarios. Results indicate that hydrogen could become a viable option already in 2030 e however, a long-term CO_2 cap is needed to sustain the transition.

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3.5 NEMESIS - New Econometric Model of Evaluation by Sectoral Interdependency and Supply

3.5.1 Short overview

The NEMESIS model (New Econometric Model of Evaluation by Sectoral Interdependency and Supply) is a sectoral detailed macroeconomic model for the European Union (Boitier *et al.* 2018). It is a system of economic models for every European country (including the United Kingdom), devoted to study issues that link economic development, competitiveness, employment and public accounts to economic policies, and notably all structural policies involving long term effects. The essential purpose of the model is to provide a consolidated framework to realise “Business As Usual" (BAU) scenarios (or other alternative scenarios), up to 30 to 40 years, and to assess the socioeconomic impact of the implementation of all additional policies not already implemented in the BAU. The main mechanisms of the model are based on the behaviour of representative agents: firms, households, government and rest of the world. From the supply side, the model distinguishes 30 different economic activities that produce goods and services through production functions and, to do so, use production factors: capital, energy, low and high-qualified labour and other intermediate consumption. All these economic activities are interrelated by inter-sectoral exchanges (conversion matrices) and external trades with other EU countries and the rest of the world. NEMESIS includes a detailed energy-environment module that allow the model to deal with climate mitigation policies, at EU and EU-national level. This module enhances the representation of the energy-system of each Member State by detailing the energy used (ten different products) by each economic activity but also by households. It also details the power generation sector by allocating electricity production between different technologies through diffusion curves. CO_2 emissions from fossil fuel combustion (FFC) are then calculated from fossil fuel consumption whereas other GHGs (CO_2 from others sources, CH_4, N_2O, HFCs, PFCs and SF_6) are either calculated by the model (however more roughly than CO_2 from fossil fuel combustion) or calibrated on external studies. Furthermore, the model can be relatively easily linked to other tools. In case of a linkage with more detailed energy-system models, NEMESIS is then used to assess the socioeconomic impacts at EU and EU-national level, with detailed characterisation of the energy-system being delegate to the detailed energy models.

3.5.2 Key features of the NEMESIS model

3.5.2.1 Geographical coverage

NEMESIS models each Member State of the European Union (including the United-Kingdom). The rest of the world is defined through a set of assumptions according to economic development, good and services prices, exchange rates, etc.

3.5.2.2 Economic activities coverage

As NEMESIS is a macroeconomic model, it covers all the economic activities in each EU Member State, but in each country the economy is divided in 30 different economic activities of which: one for agriculture, fisheries and forestry, six for utilities, thirteen for manufacturing activities, one for construction, three for transport activities and six for services (see Table 21).

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Table 21: List of economic activities covered by NEMESIS

N°	Economic activity	N°	Economic activity
01	Agriculture	16	Manufacture of food products; beverages and tobacco products
02	**Mining and quarrying expect oil and gas**	17	**Manufacture of textiles, wearing apparel, leather and related products**
03	**Oil and gas extraction**	18	**Manufacture of paper and paper products; Printing and reproduction of recorded media**
04	**Gas distribution**	19	**Manufacture of rubber and plastic products**
05	**Manufacture of coke and refined petroleum products**	20	**Other manufactures**
06	**Electricity**	21	**Construction**
07	**Water collection, treatment and supply**	22	**Wholesale and retail trade**
08	**Manufacture of basic metals**	23	**Accommodation and food service activities**
09	**Manufacture of other non-metallic mineral products**	24	**Land transport and transport via pipelines**
10	**Manufactures of chemicals & pharmaceutical products**	25	**Air and water transport**
11	**Manufacture of fabricated metal products, except machinery and equipment**	26	**Other transport activities**
12	**Manufacture of machinery and equipment n.e.c.**	27	**Information and communication**
13	**Manufacture of computer, electronic and optical products**	28	**Bank, finance, insurance & real estate**
14	**Manufacture of electrical equipment**	29	**Other market services**
15	**Manufacture of transport equipment**	30	**Non-market services**

In green: agriculture, fisheries and forestry; in red: utilities, in blue: manufacturing industries; in brown: construction; in purple: transport and in orange: services

3.5.2.3 Databases

The NEMESIS model is designed to deliver outputs in annual step. NEMESIS with its level of detail requires a big consolidated database for its functioning. Data are compiled from numerous sources (Eurostat, 2018; WIOD - Timmer *et al.*, 2015; EEA, 2019; etc.) and are post-processed for ensuring their whole accounting coherency. Thus, the dataset used by the model are frequently updated. Currently the model is calibrated for the year 2014, but for some data, historical value goes up 2017, such as for energy consumption and GHG emissions and the model can deliver output up to 2050.

3.5.2.4 The economic core

On the supply side, each sector is modelled as a representative firm determining its production level and the use of production factors (Capital, low- and high-qualified labour, energy and other intermediate consumptions) given its expectations on demands and prices. Nested CES production functions are used to characterise the production technology with substitution elasticity coming from econometric works or from literature (see Figure 11, see below). Price setting is defined under monopolistic competition, with constant margin rates, different among sectors and inter-sectoral exchanges are captured by conversion matrices that allocate the intermediate consumption (input-output matrices) and investment demands to economic activities producing the required goods and services.

Regarding households, final consumption is calculated as follows: (*i*) firstly, the aggregate consumption is computed based on the real disposable income; (*ii*) then, the aggregate consumption is allocated among 27 consumption purposes of durable and non-durable goods. The income that is not consumed results in savings, which are split between investment in real estate and financial or monetary assets.

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The labour market is modelled on the basis of the demand for labour, depending on the optimisation of production levels done by firms, and its supply, which is based on population's age and qualification levels (approximated using education levels). Wages are determined by augmented Philipps curves[19], and they are calculated separately for high- and low-qualified workers.

As for international trade, each EU country exports to (and imports from) two groups of trade partners: intra-EU and extra-EU countries. The determinants of trade are the relative prices of domestic and foreign goods and services, capturing the competitiveness effect, and the volume of exchanges, which is approximated by sectoral demand for goods and services. Different prices are set for intra-EU and extra-EU exports (and imports), to account for the differences in trade costs.

Regarding public finances, the model incorporates both subsidies and the main forms of taxation, such as taxes on production and imports, including most notably VAT, taxes on incomes and wealth, social contributions, and taxes on capital. VAT rates are modelled on the basis of the actual VAT rates (as published by European Union, DG TAXUD, 2019). Carbon price can also be introduced in the model and different recycling options can be assessed. Finally, public finance is relatively detailed allowing the model to provide indicators on government' expenditures, incomes and balances.

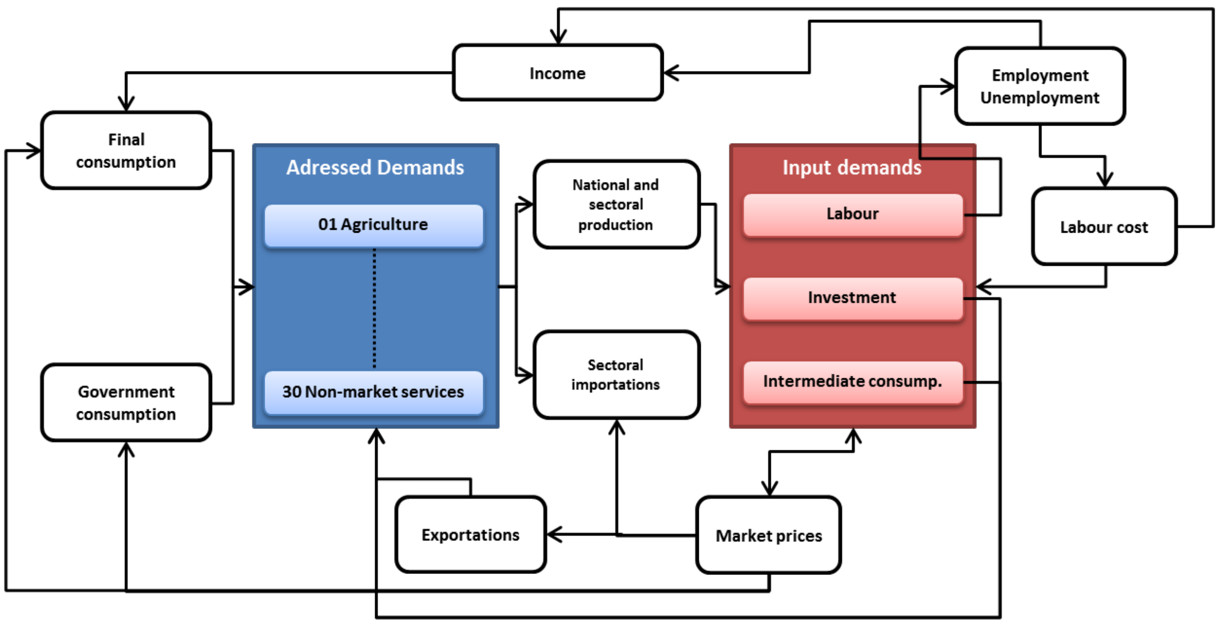

Figure 10: General scheme of the NEMESIS model' economic core

3.5.3 Energy module & emissions granularity

Besides economic core, the model includes a detailed energy-environment module. For each economic activity, the energy demand (E in Figure 11) is split, thanks to a nested CES function, in ten different energy sources (electricity, oil, gas, solid fuel, biomass including wood, biogas, biofuel and other biomass, geothermal and industrial and urban wastes). Furthermore, the "electricity" sector is not modelled as other sectors, there exists a

[19] The so-called Philipp Curves are downward-sloping curves resulting from the negative correlation between unemployment rates and inflation rates.

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specific modelling for power generation in order to properly represent energy mix capability in power generation. For this purpose, fourteen different power generation technologies are distinguished, namely: nuclear, hydro, gas, oil, solid fuel, wind (onshore and offshore), geothermal, solar (large scale PV), industrial waste and biomass and waste. Nuclear and hydroelectric power generation technologies are set exogenous because, this setting is assumed to reflect more energy policy choices of each EU member state than only pure economic choices. Other production sources are endogenous and are modelled through diffusion curves (logistic function).

Table 22: Energy products and power generation technologies covered by the NEMESIS model

Energy products	
Fossil fuels	
(of which)	**Oil**
	Gas
	Coal
Electricity	
Biomass	
(of which)	**Wood**
	Biogas
	Biofuels
	Others
Solar	
Industrial and urban wastes	

Power generation technology	
Fossil fuels	
(of which)	**Coal**
	Oil
	Gas
Nuclear*	
Geothermal*	
Hydro*	
Wind	
(of which)	**Onshore**
	Offshore
Solar	
(of which)	**PV**
	CSP
Biomass & wastes	
(of which)	**Wood**
	Biogas
	Others
Tidal	
Industrial wastes	

*In brown: CO_2 emitting technologies, in green: renewable technologies (only 50% for urban wastes) and in blue other technologies. *: production from these technologies is exogenous.*

From the energy consumption calculated, the CO_2 emissions from fossil fuel combustion can be quantified. For other emissions, except for land use emissions, either exogenous values coming from external studies are assumed or a basic modelling with emissions coefficient indexed on emitting economic activity is used (as detailed as the model allows)[20].

As the geographical coverage of the model is limited to the EU, the model does not include emissions impacts on climate such as radiative forcing. The model can only implement climate change mitigation policies on the basis of GHG emissions targets. Finally, currently the model does not currently include neither impact of climate change on the economic activity (damage function) nor climate change adaptation options.

[20] Implementation of abatement curves for these (non-CO_2) emissions, especially in agriculture, is ongoing.

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3.5.4 Socioeconomic dimensions

The socioeconomic dimension is essential in the NEMESIS, as on the one hand, it serves as drivers (exogenous variables) of the modelling simulations and on the other hand large a part of the model outputs concern socioeconomic variables. European demographics, particularly working age population, the economic context outside the EU (including GDP growth), exogenous financial variables and labour hypotheses[21] are the main drivers of the model whereas EU GDP growth is an output of the model. Nevertheless, in several multi-model analyses of climate change mitigation options, the socioeconomic characterisation of scenarios already includes GDP projections as in the case for the Shared Socioeconomic Pathways or SSP, (Riahi et al., 2017) including three sets of GDP projections (Cuaresma, 2017; Dellink *et al.*, 2017 and Leimbach *et al.*, 2017). Thus, when such socioeconomic characterisation exists the model can be constrained in order to replicate, as close as possible, the EU GDP projections.

3.5.4.1 EU demography

The first set of inputs required by NEMESIS is related to European demographics. This is essential to define the labour force and then the state of the labour market, and, to a lesser extent, its influence on the households' final consumption. For NEMESIS, the demographic data include population by age groups and by qualification for each EU country. The age groups that are distinguished are: [0-14], [15-24], [25-54], [55-64], [65-74] and [75-max]. Furthermore, demographic data for NEMESIS required the level of qualification, it is measured from two different levels of educational attainment:

- low-qualified including ISCED[22] from 0 to 4; and
- highly-qualified including ISCED from 5 to 8.

Historical data come from Eurostat (2017) while, usually, population projections by age group come from Eurostat (2018b); however alternative population projections (with short-term adjustments to ensure consistency between historical data and projections) can be used, including the SSPs (KC and Lutz, 2017) that feature projections by qualification levels (educational level attainment).

3.5.4.2 Financial exogenous variables

In NEMESIS, the capital market is not modelled and the interest and exchange rates are both exogenous. It is therefore necessary to describe the financial context in which the EU economies are expected to operate in future years. These assumptions can be modified for scenarios including specific evolutions on interest or exchange rates. In the model, while all variables are defined in euros, the exchange rates are defined (*i*) between the euro and the Rest of the World currencies and (*ii*) between the euro and the currencies of the EU countries that do not belong to the Eurozone. These assumptions are based on external studies, mainly focusing on the €/$ exchange rate. For interest rates, that are relevant mainly for the user cost of capital and agents' accounts, projections are also based on external studies or on specific assumptions related to the scenario definition.

[21] There is a version of the NEMESIS model including endogenous growth properties (see *e.g.* Brécard *et al.*, 2006 and Ravet *et al.*, 2019) however, this will not be used in the PARIS REINFORCE project, but rather a version more detailed in terms of energy and climate change mitigation options.

[22] International Standard Classification of Education 2011.

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3.5.4.3 World demand indicators and price

The Rest of the World (non-EU countries) regions are not directly modelled in NEMESIS and it is necessary to make assumptions on the evolution of global demand for the different products and on global prices of the different commodities that are traded by EU countries. Generally, the exogenous variables representing the demands for the EU coming from the rest of the World are calculated from the WIOD2016 dataset (Timmer *et al.*, 2015). The methodology uses the World Input-Output Table (WIOT), which retraces the inter-industrial exchanges between sectors, with also the geographical origin of the products used. The combination of these matrices with assumptions on the growth of GDP in the different countries outside EU allows to calculate vectors of addressed demands per country and per sector. The expected growth of GDP for non-EU countries are exogenously defined and based on external studies, SSP scenario could be used here or alternatively, GDP for non-EU countries and even sectoral value added if available could come from other models, as a part of an operational linkage between a global macroeconomic model and NEMESIS.

The second set of exogenous variables correspond to the price of the imported goods and services from the rest of the World defined for each country and sector. These are defined exogenously on the basis of past trends or on external studies when available.

The last set of exogenous variables defining the general context of the World economy is related to the prices of raw materials and notably of fossil fuels (oil, gas and coal). Here again, fossil fuel prices could be an element of linkage between a global IAM, in which fossil fuels market are modelled, and the NEMESIS model.

3.5.4.4 Socioeconomic indicators

NEMESIS can deliver numerous economic indicators at EU and country level. There are three main layers of economic indicators:

- macro-economic, such as GDP (European and EU-national) and its counterparts (final consumption, investment, exports, imports, etc.), unemployment rates, etc.;
- sectoral, such as production, value added and employment per sector; and
- agent accounts for: government, non-financial corporations, financial corporations, households including non-profit institutes serving households (NPISH), and the rest of the world.

3.5.5 Some key parameters for climate change mitigation assessment

The parameters of behavioural equations are either estimated by econometrics works or calibrated. It is the case for the production factors (capital, labour, energy and intermediate consumption), for households' consumption purposes or the wage equation that describes, roughly, the labour market functioning. Even if a large set of parameters are important when assessing EU climate change mitigation policies, we provide below some values or ranges for a restricted list of them that we assume the most important for the assessment of climate mitigation policy with the model.

3.5.5.1 Substitution elasticity between production factors

The elasticities of substitution between production factors in the nested constant elasticity of substitution (CES) production function are differentiated for each production factor and for each economic activity. Figure 11 below presents the general structure of the nested CES production function including the range of the elasticity of substitution at each level of the nesting (within brackets).

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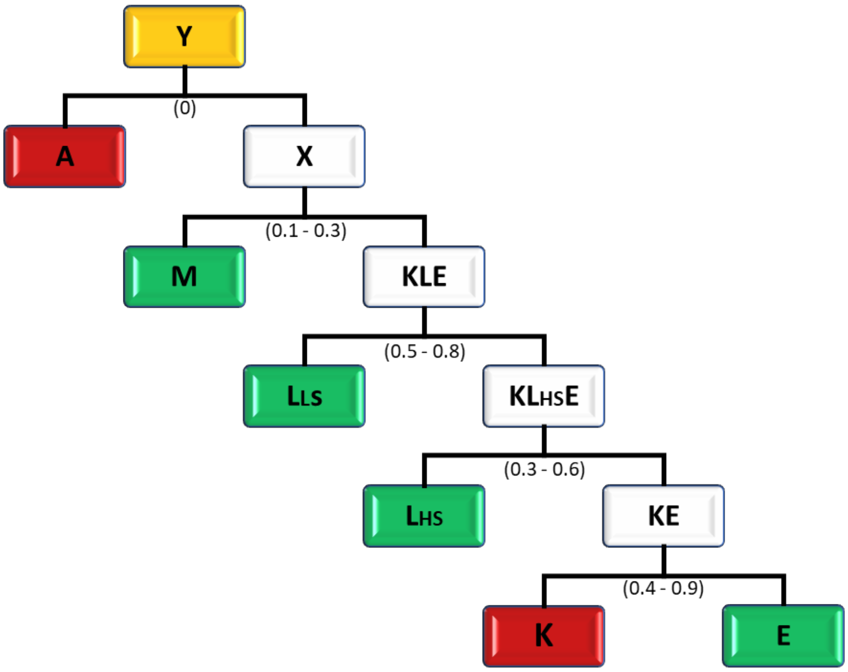

Figure 11: Structure of the nested CES production functions in NEMESIS

NB: Y is the production, A: the innovation services, X, KLE, $KL_{HS}E$, and KE are compounds inputs, M: intermediate consumptions except energy, L_{LS}: low-qualified labour, L_{HS}: high-qualified labour, K: the capital stock and E: the energy consumption.

3.5.5.2 Substitution elasticity between energy sources

Similarly, Figure 12 presents the general structure of the nested CES function allowing the calculation of the energy demand by source, with the value of the substitution elasticity that is calibrated for each economic activity.

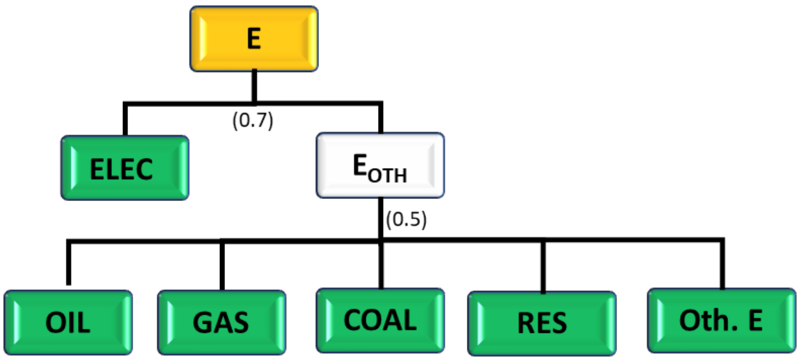

Figure 12: Energy product nested CES function

NB: E: the energy consumption, ELEC: the electricity consumption, E_{OTH}: a compound of other energy products than electricity, OIL: petroleum products consumption, GAS: natural gas consumption, COAL: solid fossil fuels consumption and Oth. E: the consumption other energy products (individualised by product).

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3.5.6 Mitigation/adaptation measures

3.5.6.1 Alone or linked

Usually, there exists two different possibilities for the NEMESIS model to deal with climate change mitigation actions either using the model including the energy and environment module or using NEMESIS linked with other modelling tools, typically more detailed and accurate to assess these actions, especially energy-system models. In the first case, climate change mitigation essentially corresponds to complying with a pre-defined annual GHG emissions binding target through the implementation of economic instruments in the model, such as carbon prices. In the second case, climate change mitigation policies are implemented (at least partially, when the linkage concerns only specific sectoral tools) in the soft-linked tool(s). This inter-linkage aims at expressing climate change mitigation costs as calculated by the coupled tool(s) in the NEMESIS model and it requires significant work to ensure consistency between variables exchanged among all tools, including in particular a proper interpretation of the meaning of these variables. Some of past studies of both settings are included in Table 23.

3.5.6.2 Climate change mitigation policies: a set of assumptions to define

Finally, and more particularly when NEMESIS is used as a standalone model, *i.e.* without linking it with other modelling tools, the implementation of climate change mitigation options requires the definition of assumptions on the policy design, on the economic instruments implemented and on what is happening in the rest of the world.

The model can deal with different economic instruments for the implementation of climate change mitigation in the EU: "universal" carbon prices, sectoral and/or nationally differentiated carbon prices, support to "green" technologies, permit allocation with different allocation rules, etc. According to the economic instruments implemented, it is also necessary to define the recycling scheme of the potential revenues produced by a new taxation (or the origin of the resources in the case of public financial supports), such as reduction of other taxes or financial compensation to economic agents, etc. All these aspects must be defined in the design of the scenario, because they will impact the outputs of the model.

Beside internal EU policy, it is also important to define what is happening in the rest of the world. Indeed, the characterisation of the socioeconomic impacts of mitigation options implemented in the rest of the world is required either on the basis of exogenous assumptions or drawing from results of interlinked global modelling tools, as it affects the output of the NEMESIS model, as presented in Section 3.5.4.2. For instance, a unilateral implementation of a stringent climate change mitigation policy in EU can have negative impacts on the competitiveness of EU firms and can even lead to new design of policy options in the EU, such as carbon border tax or free permit allowance in the EU emissions trading system (ETS).

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3.5.7 Recent publications using the NEMESIS model

Table 23: List of recent publications using the NEMESIS model

Paper	Topic	Key findings	Linkage with other modelling tools
France Stratégie, (2019)	Assessing the French social value of carbon – A multi-model analysis	The report provides a comprehensive overview of analyses enabling definition of a trajectory of values to be taken into account if we are to achieve the goal of net zero GHG emissions by 2050 in France. Among other analyses, a multi-model analysis has been achieved using two different kind of models: macroeconomic models and energy-system models. Finally, the report recommends, for 2030, to put forward a shadow price of €250 per ton of CO_2e. By 2050 it is expected to align with the estimated costs of the enabling technologies required for decarbonisation —therefore a cautious range of €600 to €900/ton of CO_2e.	No
Muller, *et al.*, (Forthcoming)	Carbon footprint of the French economy and scenarios of carbon border adjustment in EU	Based on the calculation of the carbon footprint embodied in the EU imports (done in the first parts of the report), the last part of the report presents the macroeconomic effects (on GDP and employment) in the European Union and in France of adopting carbon border adjustment mechanisms. The results show that the implementation of a tax on the carbon content of EU importations can reduce the negative impacts of stringent GHG mitigation policies, within the EU, on competitiveness and furthermore with more positive effects when incomes from this tax are redistributed to European economic agents.	No
Duscha, *et al.*, (2016)	Impact of RES deployment on employment in EU	The paper assesses whether renewable energy deployment in Europe can provide a "triple dividend", at which ambition levels of 2030 RES targets, and what the role of the support policy scheme for electricity is. It applies two types of models: a detailed techno-economic sectoral model of the deployment of RES and two macroeconomic models. Our findings suggest that up to 2030 our triple-dividend hypothesis holds even under a declining role of Europe as a technology provider for the rest of the world. More ambiguous is the order of magnitude of the effects on GDP and employment, which differs noticeably depending on the economic theory applied in the different models. Nevertheless, both models predict slightly higher GDP and employment in 2030 when implementing ambitious RES targets.	Yes (with GREEN-X a detailed modelling tool for renewables)
Enerdata, *et al.*, (2015)	"Energy-Air-Climate" scenarios for France up to 2035 (Multi-model analysis)	The report provides a quantified scenario of Energy-Air-Climate for France up to 2035. The quantification has been done with the support of different modelling tools (sectoral energy system, global energy-system, macroeconomic model). Three scenarios have been quantified: a reference scenario including existing policy instruments; a more ambitious scenario, as regards of GHG emissions mitigation including additional policy measures; and a	Yes (with POLES, an energy-system model and

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		very ambitious scenario with reinforced GHG mitigation policies. These are used as benchmark scenarios for the French climate policies. Here, the NEMESIS model has assessed the socioeconomic impact of the two ambitious scenarios in terms of GDP, employment and detailed economic activity.	micro-analyses)
Capros, *et al.*, (2014)	European decarbonisation pathways under alternative technological and policy choices: A multi-model analysis	This paper explores in a systematic manner the required energy system transformation and the associated costs incurred for the EU in order to meet the decarbonisation targets as specified in the EU Roadmap 2050, *i.e.* the 80% GHG emissions reduction target and the equivalent carbon budget by 2050. Seven large-scale energy-economy models, are employed for the simulation and quantification of alternative EU decarbonisation pathways under technological limitations and climate policy delays. The models' results show that the EU emissions reduction target is feasible with currently known technological options at low costs (lower than 1% of GDP in the period 2015–2050).	No

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