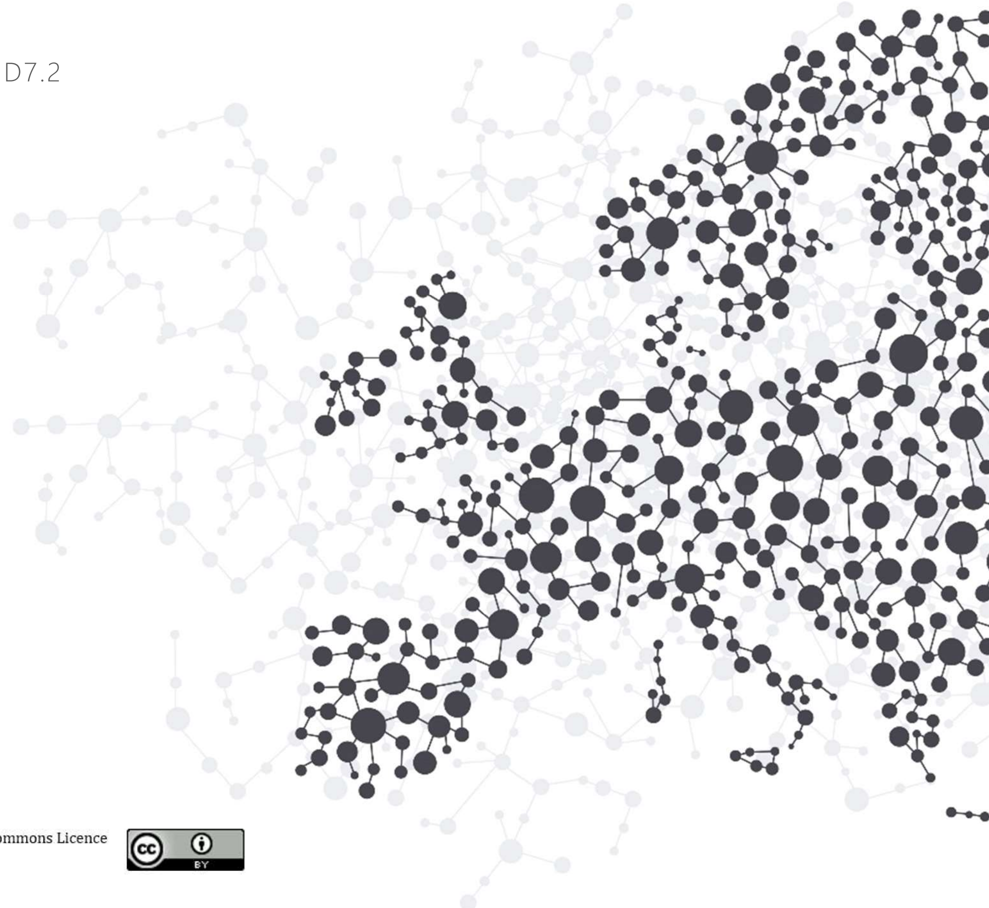
Macro-economic impacts of low-carbon transition

DELIVERABLE NO. D7.2



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 835896

Deliverable No.	D7.2	Work Package No.	WP7.3
Work Package Title	Transition Pathways		
Status	Final	(Draft/Draft Final/Final)	
Dissemination level	Public	(PU-Public, CO-Confidential)	
Due date deliverable	2022.10.31	Submission date	2022.10.31
Deliverable version	Version 1		

Deliverable Contributors:	Name	Organisation	Date
Deliverable Leader	Hettie Boonman	TNO	2022.10.31
Work Package Leader	Pedro Crespo del Granado	NTNU	
Contributing Author(s)	Hettie Boonman	TNO	
	Paolo Pisciella	NTNU	
	Frédéric Reynès	TNO	
Reviewer(s)	Ryan O-Reilly	JKU Linz	2022.10.24
	Giulia Garzon	JKU Linz	2022.10.24
Final review and approval	Ingeborg Graabak	SINTEF Energy Research	

History of Change

Release	Date	Reason for Change	Status

DISCLAIMER / ACKNOWLEDGMENT

The content of this deliverable only reflects the author's views. The European Commission / Innovation and Networks Executive Agency is not responsible for any use that may be made of the information it contains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 835896.

Table of Content

Contents

List of Tables

List of Figures

Executive Summary

The mitigation of the increasingly visible consequences of global warming and climate change is one of the biggest challenges facing humankind. A global effort is necessary to implement actions and strategies that limit greenhouse gas emissions in the future. For this, the dialogue between policy makers, researchers and industry needs to be improved. OpenENTRANCE aims to help in this dialogue by presenting transition pathways that visualize (qualitatively and quantitatively) four different ways to establish a low carbon-emission energy system. For this, an ICT platform has been developed in order to gather and facilitate the interaction between a wide selection of modelling tools and data that cover the multiple dimensions of the energy transition.

This deliverable presents the main results of Task 7.3: *Comparative macro-economic analyses of the energy transition*. This task is part of WP7: *Transition Pathways*. WP7 analyses energy transition pathways in order to explore the effects of different strategies to decarbonize the energy system between 2020 and 2050. In particular, WP7 studies the societal impacts and consequences of the transformation of the energy system. Using the consistent pathway descriptions developed in Task 7.1 and 7.2, Task 7.3 investigates the impacts of the energy transition on the overall economy (macroeconomic and sectoral perspective). To do so, it compares the results of two "top down" macro-economic Computational General Equilibrium (CGE) models that provide information on the overall economic effects of the implemented scenarios, like changes in GDP and sectoral production levels, prices, trade and societal welfare. The effects on demand, welfare and distribution in different sectors are also analysed.

The two CGE models used are REMES-EU and EXIOMOD. REMES-EU developed by NTNU is a multi-region, multi-sector CGE model that covers European countries (EU27+). It focuses on economic policies on financing large-scale investments and the effectiveness of the policy instruments used. EXIOMOD 2.0 developed by TNO measures the environmental and economic impacts of policies by accounting for the economic dependency between sectors. It is a global and multi-country model (44 countries & 5 regions) with bilateral trade flows between countries at the detailed commodity level. EXIOMOD uses the EXIOBASE 2.0 database that covers a high level of detail on economic sectors (up to 200 products). EXIOMOD 2.0 is based on a flexible modular approach that allows for using environmental extensions on emissions, resources, water and land use and to conduct both Input-Output analysis and CGE simulation.

Storylines and scenarios

The models make use of four storylines, that is, four possible future energy scenarios. The names of the four openENTRANCE scenarios are:

- ***Directed transition*** (DT) where the key drivers are: technological novelty and policy exertion.
- ***Techno-Friendly*** (TF) where the key drivers are: technological novelty and smart society.
- ***Societal commitment*** (SC) where the key drivers are: smart society and policy exertion.
- ***Gradual development*** (GD) where there is a middle way combination of the 3 key drivers: technological novelty, smart society and policy exertion.

A fifth storyline is developed in this deliverable, the reference scenario, which corresponds to a business as usual situation. There was a need for a business as usual situation, since the four openEntrance storylines are all very ambitious in reaching the climate goals (GD aims at reaching an at most 2 degrees temperature increase, and DT, TF and SC aim at reaching at most 1.5 degrees increase). The development of a reference scenario allows us to compare several decarbonized worlds by 2050 with a situation where there are only little changes in our lifestyle and production methods. The reference scenario is based on EU Reference Scenario of the European Commission (Capros et al., 2016).

The storylines are initially evaluated by GENeSYS-MOD, a techno-economic bottom-up energy system model. This model provides insights regarding investment decisions and quantities for all technologies, energy flows and emissions for the electricity and transport sector (see openENTRANCE Deliverable 7.1: European storylines for low carbon futures of the European energy system, Auer et al., 2019). EXIOMOD and REMES-EU combine data received from GENeSYS-MOD with parameters defined in accordance with the openENTRANCE storylines to compute the socio-economic impacts of such storylines.

Linking of models and scenario assumptions

The communication between the energy model and two macro-economic models takes place via a selection of variables. The most important variables are: (1) technology mix of electricity production (2) the energy mix in three important industries; services, transport and manufacturing industry (3) and energy mix for households.

In addition, extra scenario assumptions have been made in order to align with the vision underlying each of the storylines. In SC, it is assumed that society is motivated to make a transition that goes beyond the energy transition by implementing a transition to a circular economy. Thus, this scenario assumes an extra high uptake of circular business models. In the two scenarios (SC, DT) where policy interventions are assumed to be an important element in reaching decarbonized future there are subsidies to support the use of electricity, and a tax to discourage the use of fossil-based fuels. Scenarios TF and DT assume that technology novelty is a driver to reach decarbonization, therefore it is assumed that these scenarios are able to reach an extra strong energy efficiency due to innovations.

Main results

Our results can be divided into economic and environmental effects. Under the header of economic effects, we show the impact of the four decarbonisation scenarios on gross domestic product (GDP), industrial output, electricity demand, demand for fossil-based fuels, price levels and final consumption of governments and households. The environmental effects are represented via the CO2 emissions. All the effects are measured by comparison to the reference scenario where no climate policies are implemented. In this section we only highlight the most important results.

Economic effects

- GDP in 2050 in all decarbonization scenarios is fairly similar to GDP in the reference scenario. Due to energy efficiency, scenarios DT and TF have a slightly higher GDP than the other scenarios.
- Including climate change effects in the scenarios has a negative effect on GDP for all scenarios, but mostly in the reference scenario where no climate policy is implemented. However, this effect is still limited in 2050 because the temperature increase is expected to deviate between the scenarios mostly between 2050-2100.
- The industrial output of almost all sectors decreases under a tighter carbon cap. The reference scenario assumes only a CO2 cap that decreases emissions by 40% with respect 1990 carbon emission levels. The other scenarios assume a reduction between 80% and 95%. The four openENTRANCE scenarios therefore show lower industrial activity compared to the reference scenario in 2050.
- There are two sectors that increase in industrial activity compared to the reference scenario: the electricity sector(s) and the service sector. The growth in the electricity sector is facilitated through the shift away from fossil-based fuel sources towards electricity.. The service sector increases due to new circular economy business models, where leasing structures replace the old business model of owning a product. This latter effect is most dominant for scenario SC.
- Macro-economic model REMES-EU gives a slightly higher uptake of hydrogen compared to EXIOMOD, because under the modelling assumptions of REMES-EU after 2035 purchase of hydrogen becomes more economically feasible than electricity.
- Demand for electricity is higher in the four decarbonisation scenarios compared to the reference scenario for multiple reasons: (1) a stricter carbon cap to reach the temperature goals results in a shift towards cleaner energy substitutes, i.e. electricity (2) information from GENeSYS-MOD also exogenously forces certain industries (services, manufacturing, and transport) in the model to shift towards cleaner energy substitutes (3) the uptake of hydrogen requires a lot of electricity as input for the production process.

- The increase in electricity demand is compensated with the decrease in demand for fossil-based fuels.
- The two models behave differently in terms of price development. For more information see Section 3.8.

Environmental effects

- Under the four decarbonisation scenarios, CO2 emissions are decreasing intensively over the years. The most important driver for this decrease is the cap on carbon. Under the reference scenario, the cap on carbon was less strict.
- In earlier years (2020-2030), the cap on carbon is not always binding because the reduction in CO2 emissions can also be achieved by technological progress (e.g. energy efficiency measures and carbon intensity reduction assumptions), policy decisions (e.g. subsidies and taxes on the energy products). Under these circumstances, there is not yet a need to put a price on the emission of carbon dioxide. However, when the cap becomes stricter starting from 2040, the high price of polluting emissions becomes the strongest incentive for industries to shift towards cleaner energy substitutes.
- The carbon cap increases exponentially in the years 2040-2050 for both macro-economic models.

1. Introduction

The Paris Agreement signed in December 2015 during the COP 21 (2015 United Nations Climate Change Conference) has the ambition to limit the global temperature increase to 1.5°C compared to pre-industrial levels. Except during the 2020 COVID pandemic, global emissions have been increasing since 2015. The Intergovernmental Panel on Climate Change (IPCC, 2021) estimates that with the current global carbon emissions of more than 50 gigatons per year, the carbon cap for the 1.5 °C target will be exhausted in less than a decade, whereas the cap for limiting to 2 °C will be met in two decades. Meeting theses target requires a big effort both for developing and advanced countries which have to implement a rapid and major change in the structure of their supply and demand for energy. This will have an important impact on energy sectors but also on the rest of the economy.

It is therefore useful to evaluate the economic impact of alternative energy transition scenarios. In this report, we simulate the economic and environmental impact of the four openENTRANCE scenarios (Deliverable 7.1 developed in WP7, Auer et al., 2019). All scenarios align with the mid-century climate goal defined in the Paris Agreement, however, the transition pathway differs between scenarios. (1) In the Directed transition (DT) scenario, the key drivers are technological novelty and policy exertion; (2) In the Techno-Friendly (TF) scenario, the main drivers are technological novelty and smart society; (3) In the Societal commitment (SC) scenario, the drivers are smart society and policy exertion; (4) the Gradual development (GD) scenario combines all three drivers.

We use two Computable General Equilibrium Models (CGEM), EXIOMOD and REMES-EU, to quantify the economic and environmental impacts of these scenarios between 2020 and 2050. The results of the four decarbonisation scenarios are compared to a reference scenario that represents a business as usual situation. While the models compute the whole trajectory between 2020 and 2050, we will summarize the results for 2050 only.

Note that the analysis is based on equilibrium considerations, and as such, we do not attempt at estimating or predicting a possible future development of important macroeconomic indicators. Instead, these type of models and scenarios are useful for guiding policy-making, to define the framework to detect important mechanisms that might explain why indicators behave in a certain way as a consequence of the development of a given decarbonisation scenario.

The report is organized as follows. Section 2 describes briefly the scenarios that are simulated. In addition, the quantified input for each scenario is given along with the motivation for each scenario framework. The model descriptions are also provided in Section 2. Section 0 presents the simulation results while Section 0 concludes.

2. Methodology

2.1 Scenario description

One of the biggest challenges facing mankind is limiting global temperature increase below 2°C. For this, a global effort is necessary to limit greenhouse gas emissions as much as possible. In December 2015, global leaders met in Paris to make a binding agreement on reducing their greenhouse gas emissions. Via national determined contributions (NDC's), countries announced their intended climate actions. An important component of the openENTRANCE project is the definition of realistic and consistent storylines compatible with the Paris Climate Agreement (Deliverable 7.1 of openENTRANCE project, Auer et al., 2019).

Many storylines and scenarios have been developed in the past (for example SSP and RCP scenarios from IPCC (O'Neill et al, 2017), Energy Roadmap 2050 scenarios (Decker and Vaskov, 2011), EUCO scenarios, 'a clean planet for all' scenarios (Capros et al., 2018)). The openENTRANCE storyline descriptions are founded on a thorough analysis of these renowned global and European pathway and scenario studies.

A review of existing storylines, scenarios and pathways shows that we are confronted with different kinds of uncertainties when trying to describe the future energy system. For the development of the storylines, three key uncertainties were chosen as main drivers of the openENTRANCE storylines:

- **Society's attitude and lifestyle.** How flexible will the individual and society be, and how seriously do they take responsibility for transitioning towards a low-carbon energy world? Under a '*smart society*', engagement and awareness of society to undertake concrete actions is maximized.
- **Novelty and availability of technologies.** Technological progress has always been a big uncertainty. Will technological progress develop fast enough to support a smooth transition towards a low-carbon energy world? Under '*technological novelty*', innovation and technological breakthrough help to foster the energy transition.
- **Geopolitical and economic development.** Will there be a smooth global energy transition towards a low carbon society accompanied by harmonious geopolitical developments that support the transition? Or will it be a disruptive global energy transition with geopolitical tensions and uneven distribution of economic prosperity? Under '*policy exertion*', the world is steered towards a low-carbon energy world via implementation of effective policy measures.

In openENTRANCE, four storylines have been developed. Each storyline is defined by a combination of two key drivers/ uncertainties (see Figure 2-1). The names of the four openENTRANCE scenarios are:

- ***Directed transition*** (DT) where the key drivers are: technological novelty and policy exertion.
- ***Techno-Friendly*** (TF) where the key drivers are: technological novelty and smart society.
- ***Societal commitment*** (SC) where the key drivers are: smart society and policy exertion.
- ***Gradual development*** (GD) where there is a combination of the 3 key drivers: technological novelty, smart society and policy exertion.

In the rest of the report, we will regularly refer to these scenarios via their abbreviations DT, TF, SC, and GD.

The developers of the storylines do not have a preference towards anyone of the scenarios and acknowledge that they are all possible.

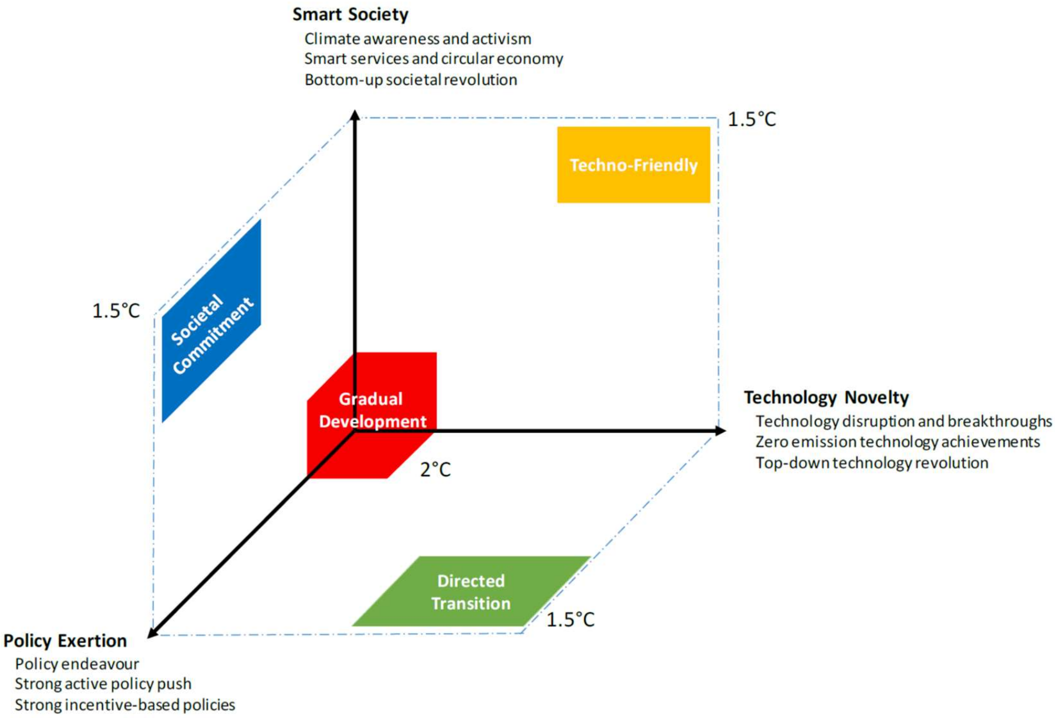


Figure 2-1: openENTRANCE storylines typology = policy exertion x technological novelty x smart society. Source: openENTRANCE project D7.1 (Figure 4.2).

While Figure 2-1 describes the storylines, we should also make a clear distinction between storylines, scenarios and pathways. ***Storylines*** are narratives that qualitatively describe a possible energy future. A storyline encompasses a variety of quantitative ***scenarios*** that reflect different possible options, strategies and technological potential. A scenario is constructed through model inputs (e.g. parameter settings) and are tailor made for a specific storyline. ***Pathways*** are numerical evaluations of scenarios, for example the outputs of an energy or macro-economic model.

This deliverable uses the storylines developed in Deliverable 7.1 (Auer et al., 2019). For each *storyline,* one *scenario* is developed, resulting in quantitative model input for the two macro-economic models. For the quantification step, Tables 4.2(a)-4.2(d) in Deliverable 7.1 were used as a guide. These tables give for each storyline, a wide range of parameters that qualitatively describe a future. In addition, the scenarios for the macro-economic models were also shaped by using model output of energy model GENeSYS-MOD. Namely, GENeSYS-MOD is the key energy system model qualified to deliver the tailor-made quantified openENTRANCE scenarios. More explanation on the quantification steps for the scenario input is given in Section 2.3.

The result of this report is five macro-economic *pathways*, corresponding to the four openENTRANCE storylines and one additional reference that represents the business-as-usual (BAU) situation. The BAU corresponds to the pathway where the policy, technological and societal developments diverge from a low carbon transition and are therefore incompatible with the Paris agreement.

2.2 Description of Models

2.2.1. A general description of a computational general equilibrium model

Let us start by explaining the main mechanisms of a CGE model. This type of model assumes that the 'optimal solution' is found when total demand of the economy equalizes total supply. That is, all that has been produced somewhere in the economy (via domestic production and imports) needs to be consumed somewhere else (via final consumption of households and governments, investments or via export). This is also illustrated in Figure 2-2, which gives the general structure of a CGE model.

To ensure the equilibrium between supply and demand, an assumption regarding the "closure" of the system has to be done. Existing CGEMs generally choose between two main closures. The Walrasian closure assumes that perfect price flexibility ensures the instantaneous equilibrium between supply and demand. On the contrary, the Keynesian closure assumes that demand defines supply whereas price and quantities are rigid and adjust slowly to the optimum.

In the base year (e.g., the year of the database underlying to the model), the model is always in equilibrium. When a scenario for 2020-2030 is implemented, 'shocks' are implemented to the model, which initially bring the model out of equilibrium. An example of a shock is the transport sector that changes its energy consumption, e.g. shifting from gasoline to electricity. Prices indices are an important instrument to bring the model back to a state of equilibrium. Prices, production levels and consumption levels all change a little such that the model goes back to the equilibrium state where total supply equals total demand.

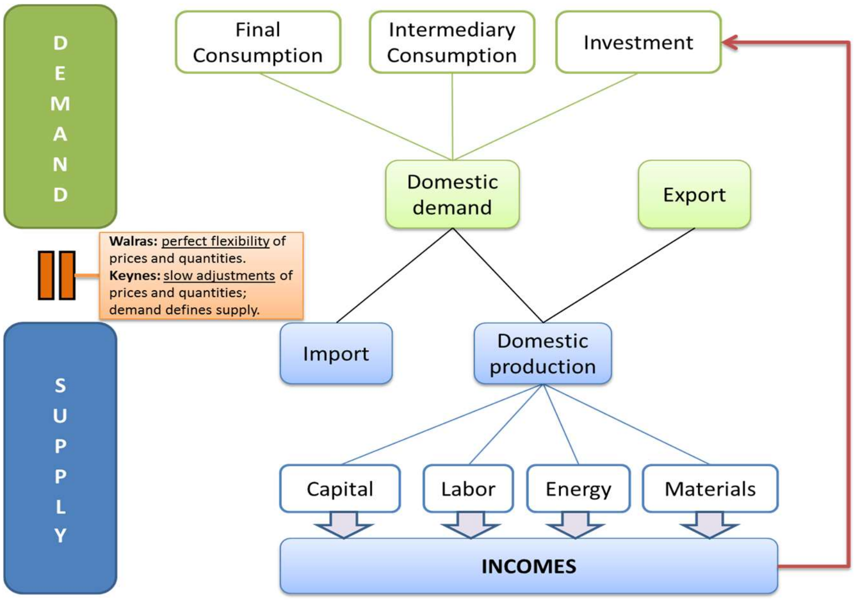


Figure 2-2: General structure of a CGE model

2.2.2. Model descriptions

EXIOMOD 2.0 is developed by TNO, Netherlands. It is an economic model that measures the environmental and economic impacts of policies. As a multisector model, it accounts for the economic dependency between sectors. It is also a global and multi-country model with consistent bilateral trade flows between countries at the detailed commodity level. Based on national account data, it can provide comprehensive scenarios regarding the evolution of key economic variables such as GDP, value-added, turn-over, (intermediary and final) consumption, investment, employment, trade (exports and imports), public spending or taxes. Thanks to its environmental extensions, it makes the link between the economic activities of various agents (sectors, consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases).

The REMES-EU model is developed by NTNU/SINTEF in Norway. It represents a multi-regional, multi-sectoral Computable General Equilibrium model. It has been designed primarily to analyse the impacts of different climate policy measures and the interactions between the economies of the European Countries. In considers the explicit evaluation of fossil resources extraction and considers the price for CO2 as endogenous by linking it to the CO2 allowances available in each given period. The model is flexible in term of its input structure and can accommodate different geographical and sectorial specifications and it allows for a flexible modelling of new sectors.

More detailed model descriptions can be found in the appendix.

2.2.3. Comparison of the models

EXIOMOD and REMES-EU are both macro-economic models, however with different underlying assumptions and equations. This section points out the main differences between the two models.

This section focuses on differences in underlying database and modelling choices for consumption, production, trade and closure modules, differences in nesting structures and corresponding elasticities, and finally differences in how the different scenarios are implemented in the models. The latter is partly dependent on model restrictions.

Differences in database.

While both EXIOMOD and REMES-EU use EXIOBASE as underlying database, there are still differences in the version number, base year and aggregation level of underlying data. Table 2-1. gives basic information on the version of EXIOBASE used for the models.

Table 2-1: Main characteristics of Supply and Use tables underlying to EXIOMOD and REMES-EU

	EXIOMOD	REMES-EU
Base year	2011	2007
Format multi-regional data	Social Accountancy Matrix	Social Accountancy Matrix
Number of regions	49 (44 countries among which the 27 EU regions, and 5 aggregated RoW regions)	29 (EU27 without Croatia but with the inclusion of Norway, Switzerland and Great Britain)
Number of products	200	32
Number of industries	163	24

Both models have the option to further aggregate regions, products and industries. Given that the aggregation level of the base data is slightly different, aggregation level of the modelled regions, products and industries also have subtle differences. For example, EXIOMOD has the option to consider somewhat more disaggregated electricity sectors (e.g., electricity by wind, electricity by coal, electricity by geothermal, etc.), while the database of REMES-EU only considers one electricity sector. It was chosen to keep the disaggregated electricity sectors in EXIOMOD, because it facilitates the implementation of scenarios in the model. Table 2-2 shows for each model the modelled industries, and Table 2-3 the modelled commodities.

Table 2-2: Assumptions on aggregation industries for EXIOMOD and REMES-EU

Description	EXIOMOD	REMES
Agriculture	iAGRI	iAGRI
Coal extraction	iCOAL	iCOAL
Crude oil and natural gas extraction	iCOIL	iCOIL
Manufacturing industry	iINDU	iINDU
Aluminium production	iALUM	iALUM

Electricity	iELCT	iELCT
Trade and distribution services of electricity	iTRDI	iTRDI
Natural Gas	iNG	iNG
Services	iSERV	iSERV
Transport services	iTRAN	iTRAN
Production of electricity by coal	iELCC	---
Production of electricity by gas	iELCG	---
Production of electricity by nuclear	iELCN	---
Production of electricity by hydro	iELCH	---
Production of electricity by wind	iELCW	---
Production of electricity by petroleum and other oil derivatives	iELCO	---
Production of electricity by biomass and waste	iELCB	---
Production of electricity by solar photovoltaic	iELCS	---
Production of electricity (not elsewhere classified)	iELCE	---
Production of electricity by Geothermal	iELCT	---
Production of hydrogen – electrolyser	iH2	iH2E
Production of hydrogen – steam reform		iH2S
Production of hydrogen – steam reform with CCS		iH2C

Table 2-3: Assumptions on aggregation commodities for EXIOMOD and REMES-EU

Description	EXIOMOD	REMES-EU
Agriculture	pAGRI	pAGRI
Manufacturing industry	pINDU	pINDU
Aluminium production	pALUM	pALUM
Services	pSERV	pSERV
Transport services	pTRAN	pTRAN
Electricity	pELEC	pELEC
Trade and distribution services of electricity	pTRDI	pTRDI
Steam and hot water supply	pHTWT	pHTWT
Crude Oil	pOIL	pOIL
Gasoline	pGSL	pGSL
Diesel	pDSL	pDSL
Heavy distillate	pHDI	pHDI
Natural gas	pNG	pNG
Coal	pCOA	pCOA
Biofuels	pBIO	pBIO
Other fuels	pFUL	pFUL
Hydrogen	--	pH2

Hydrogen sector

The models and underlying databases initially did not include a sector that produces hydrogen. This sector was included by both models in a slightly different manner.

EXIOMOD

In order to include this sector, it was assumed that sector production of natural gas (iNG) and sector production of hydrogen (iH2) basically provide the same product: gas. The difference between the two sectors lies in the production technology. Therefore, the newly introduced hydrogen sector also produces the product gas (pNG) but the GHG emissions intensity decreases when the share of gas produced by the hydrogen sector increases.

The production structure of the sector was created given data from James et al., 2016. There was no production of hydrogen in EXIOMOD in the base year. Therefore absolute (but negligible) amounts were added to the base year in order to construct the production structure of hydrogen. What matters most is the relative division of costs for the hydrogen sector. Table 2-4 gives for all regions the production structure of iH2. The production structure is created based on the simple average of three technologies that can be used to produce hydrogen, steam reforming, steam reforming plus CCS, and electrolysis.

Table 2-4: Production structure of hydrogen sector in EXIOMOD

Input of commodity / production factor	Percentage of cost in hydrogen sector
Services	5%
Manufacturing industry	11%
Electricity	44%
Natural gas	12%
Capital	25%
Labour	4%
Total	**100%**

REMES-EU

REMES-EU considers the hydrogen production based on three possible technologies: (1) electrolysis, (2) steam reformation and (3) steam reformation with carbon capture and storage. Each of these technologies defines a production sector that is not active in the base year, but that can become active and start producing in future time periods depending on the relative demand for such commodities. Each hydrogen sub-sector is characterized by a different production technology and will need different inputs. The development of the prices of the different input commodities will make some of the technologies more profitable than others, leading to different production mixes for hydrogen towards 2050.

Table 2-5 shows how the impact that the cost of each input has per unit of revenue. As it can be noticed the sum of the costs is larger than 100%, which means that at the base period the costs are higher than the revenues (standardized to unit) and for this reason, the sectors will not yet produce in the base year. Production will only start if the prices of the different inputs and the price of hydrogen will change so that the unit revenues cover the unit costs. Data for the costs have been taken from James et al., 2016, while the change in capital, labour and electricity requirement for the production of hydrogen via Steam Reformation with CCS has been defined according to the approach in McFarland and Herzog, 2006. The unit revenue has been assumed to be 3€ per kg at the base year (the base year of REMES-EU's underlying database is 2007) to be competitive with other fuels. The ratio between the cost of each input and the unit revenue gives the percentages in Table 2-5.

Table 2-5: Production structure of hydrogen sectors in REMES-EU

Input of commodity / production factor	Steam Reformation	Steam Reformation with CCS	Electrolysis
Services	7%	7%	3%
Manufacturing industry	19%	19%	1%
Electricity	0%	13%	115%
Natural gas	25%	25%	0%
Capital	45%	49%	18%
Labour	7%	7%	3%
Total	**103%**	**121%**	**140%**

Differences in underlying equations and assumptions.

The main differences between the two models are described in Table 2-6.

Table 2-6: Main differences in modelling assumptions between EXIOMOD and REMES-EU

Description	EXIOMOD	REMES-EU
Nesting structure	KLE nesting structure. Where M is linked with KLE via a linear Leontief function.	KLEM nesting structure for all sectors besides for extraction sectors (oil, gas and coal) using a KLEM-R structure, where the KLEM aggregate is further aggregate with specific capital representing the availability of the extracted resource. A similar structure is devised for refineries to model their possibility to operate only in presence of a mineral resource.

Rest of the World	Rest of the World regions are modelled.	Rest of the world regions are not modelled but are connected to the European regions via transfers and exogenous defined export and imports, assuming trade is balanced.
Household utility	CES consumption function was used for openENTRANCE. The model has option to switch to LES-CES.	A Cobb-Douglas function is used to model household consumption preferences.
Government and Investment	CES consumption function	A Cobb-Douglas function is used to model the government and investment consumption preferences.
Household energy use	EXIOMOD uses CES consumption function with only one nest for household consumption.	Energy use is modelled as the other commodities using a Cobb-Douglas function. Power transmission and Power are sub-nested using a Leontief structure and each fossil fuel is sub-nested with the related CO2 allowances using a Leontief structure.
Carbon Cap	See appendix D.	See Appendix D.
Timestep	1-year timestep.	5-year timestep.
Elasticities	The elasticities for nests KLE and KL are chosen equal between the two models (Koesler Schymura, 2015). The elasticities within the energy nest are set to 3 for all sectors, except for iELCC, iELCG, iELCO, where switching to other fuel inputs is not realistic. The elasticities of these sectors should be very low. For example, under a high elasticity it could imply that the sector 'electricity by coal' ('iELCC') changes its production structure (i.e. energy inputs) to other types of energy than coal. This is not in line with the definition of this sector. EXIOMOD does not set elasticities to a lower lever when external data from GENeSYS-MOD is used.	Elasticities for each production function of the production sectors are taken from Koesler Schymura, 2015 and applied to the KL subnest, KLE subnest and KLEM subnest. Energy inputs are aggregated using a high elasticity of substitution (equal to 5) to ensure a transition of the energy sources as a consequence of decarbonization policies. Unless there is external data from GENeSYS-MOD and then these elasticities are set to 0.1. Materials are aggregated according to a Leontief function. When the additional nest for resources is included, it is aggregated to the remaining function using a low elasticity as the natural resource cannot be exchanged with other inputs but must be in the production input list.

2.3 Quantitative input for models

Along with the qualitative descriptions of the storylines a concise factsheet has been developed with the main elements of each storyline (see Tables 4.2(a)-4.2(d) in Deliverable 7.1, Auer et al., 2019). It consistently summarizes the storylines for a range of variables, i.e. storyline features. This fact-sheet is used to translate the qualitative storylines into quantitative input for the models.

Table 2-7 translates the qualitative elements of the storylines defined in Deliverable 7.1 into quantitative inputs for the linkage with macro-economic models REMES-EU and EXIOMOD. It highlights the assumptions behind the linkages and the exogenous sources that have been used. The second column of the table refers to sheet-names in Excel files that give quantified scenario inputs to the model. These files are included as supplementary documents to the report.

Table 2-7: Linking qualitative storyline features to quantified model input, including the motivation and references of the quantification.

Storyline features	Reference to quantified input sheet	Motivation of linkage and sources
Geopolitics		
Performance of Global Economy/Markets	- GDP - GDP_ROW - Population - POP_ROW	GDP of European regions always grow with the EU-reference scenario. When a scenario says 'uneven distribution of economic wealth', the developing regions outside Europe grow with expected growth from OECD scenario. When scenario says 'global prosperity', the developing regions outside EU grow slightly faster to catch up with developed regions.
Global/International Climate Policies	- CO2_cap	Cap on CO2 is assumed to decrease by 40% in the reference scenario, by 70-80% in the Gradual development scenario, by 80-90% in the Societal Commitment and Directed Transition scenario, by 90-100% under the Techno-Friendly scenario. Reductions are with respect to the base year 1990 and implemented for European regions only. The reductions are taken from element 'GHG emission reduction' in Tables 4.2(a)-4.2(d) in Deliverable 7.1, Auer et al., 2019.
Markets/Economic Development		
Resource Exploitation	- Materials	A shift from the use of materials to the use of services. Depending on the scenario, all countries join in the servitization[1] process or only a selection of countries. For the Gradual Development scenario, most of the countries reduce their preference on materials by 20%, moving this preference towards services. In the Societal Commitment this amount goes to 35%. Under the Techno-Friendly scenario, this reallocation is only equal to 5%.
Circular Economy: Level of Importance	- Materials	See above under Resource Exploitation.
Climate and Energy Policies		

[1] Servitization is defined as the 'transformational processes whereby a company shifts from a product-centric to a service-centric business model and logic" (Kowalkowski et al., 2017).

Preferable Climate and Energy policies	- Taxes and subsidy on use of fuels	Under DT and SC, climate goals are reached due to stricter policies. For these scenarios there is a subsidy on the use of electricity (5%) and an additional tax on the use of unsustainable fuels (5%).
GHG emission reduction targets	- CO2 cap - Carbon efficiency	Both models implemented a CO2 cap (also see Global/ International Climate policies). In addition, the models have implemented for all scenarios a reduction trajectory of carbon efficiencies. This represents the reduction in emissions due to decarbonization efforts in industries. The carbon efficiency quantification assumption has been taken from the EU reference scenario (Capros et al., 2016).
Incentives for Research&Development/ Pilots	- Energy_efficiency	R&D efforts make industries more energy efficient. The level of efficiency is the same for every scenario, including the reference and GD. This quantification assumption has been taken from the EU reference scenario (Capros et al., 2016).
Technology Portfolio in Energy & Transport		
Role of Existing/ Known/ Novel Technologies: Candidates (Production, Complementary)	- Energy_use_transport - techmix	We take technology mix for production of electricity from GENeSYS-MOD scenario (sheet 'techmix'). Note that REMES-EU and EXIOMOD use these values in a different manner because REMES-EU has one power sector, where EXIOMOD differentiates between 10 different types of electricity, defined by the technology that produces the electricity. The details on usage of the external information for each model will be explained in the tables placed further in the document. The type of energy used for transport is taken from GENeSYS-MOD scenario (sheet 'energy_use_transport').
Society's Attitude & Lifestyle		
Contributions to Circular Economy	- Materials	See above, under resource exploitation and circular economy.
Energy Sectors (Electricity, Heat/Cooling, Gas/Fossils)		
Resources	- Oil_extraction_level	This scenario element is only implemented in REMES-EU. In the reference scenario, the factor that influences the oil extraction decreases by 10% every five years. For the other scenarios this is 15% every five years.
Sub-Sectors (Structure, Demand): Industry	- Energy_efficiency - Energy_use_industries	Industries switch to different energy input types. This data is taken from the GENeSYS-MOD for scenarios GD, TF, DT and SC (Energy_use_industries). The reference scenario does not assume an external input for the shift in the use of energy. In addition, industries also become more energy efficient.
Sub-Sectors (Structure, Demand): Commercial/ Tertiary	- Energy_use_hh_and_serv	Households and services switch to different energy input types. This data is taken from the GENeSYS-MOD for scenarios GD, TF, DT and SC (Energy_use_hh_and_serv). The reference scenario does not assume a shift in the use of energy.

More details on how the scenarios are implemented in the two macro-economic models can be found in Appendix C. The models have their own specific features, and therefore the implementation of the scenarios can deviate slightly depending on the model. Also, note that some measures or behavioural changes occur 'manna from heaven', i.e. without a cost. In future research it would be interesting to see how the results would change if also this switching cost-component is taken into account.

3 Results

This section presents the results of the four openENTRANCE scenarios and compares them with the reference scenario. The reference scenario presents the business-as-usual situation, based on the EU Reference Scenario (Capros et al., 2016), where only minimal carbon reduction measures are implemented (see Section 2.3). In the other four scenarios, either the target of temperature increases below 2°C (gradual development) or below 1.5°C (Technological Change (TC), Societal Commitment (SC) and Techno Friendly (TF)) is implemented. The motivation behind the development of the reference scenario is twofold: first and foremost, it is used as realistic business-as-usual scenario used to compare the other 2050 scenario results. The reference scenario is assumed to have a much milder decarbonization towards 2050, while all four openENTRANCE scenarios have a strong decrease in carbon emissions. Moreover, the reference scenario is used to calibrate some of the parameters such as labour productivity that remain the same across scenarios while ensuring that the GDP growth of the reference scenario reflects the one featured in the EU Reference Scenario (Capros et al., 2016).

Section 3.1 to 3.8 present the macro-economic results for a selection of model outcomes. In each of these sections, model outcomes are compared and differences between the models explained.

Most figures and tables present the model outcomes in indices with respect to 2020[2] or percentage change in 2050 with respect to the reference scenario – rather than in million euros for two reasons. First, it makes it easier to compare across the two models. While the models both use EXIOBASE as underlying dataset, the version and base year of the data is different. On top of that, small modifications or additions to the databases have been made to calibrate the two different CGE models. For more information, see Section 2.2.2 and 2.2.3 for comparison of the two models and databases. Second, when comparing growth or declines of different sectors in one figure, an index makes comparison easier. For example, the manufacturing industry is a very large sector and wind energy is quite small. When this figure is presented in million euros, the size differences between sectors make the analysis of the results for the smaller sectors impossible.

Each of the models specifically model the 27 countries in the EU. For illustration purposes, it is chosen to present the results in this section for the aggregated region EU-27.

[2] Let us explain, using an example, how indices with respect to 2020 are calculated. Assume that the models produce trajectories for GDP for the EU between 2020 and 2050 in million euros. However, we are only interested in the *relative changes* between 2020 and the subsequent years, and not in outcomes in million euros. In that case, we divide the whole time series by value of GDP in the EU in 2020. We now have created an index with respect to 2020. When the value of this index is 1.6 in 2050, it means that GDP has increased by 60% relative to the level in 2020.

3.1 Gross Domestic Product

Box 3.1: summary of GDP results

The measures that have most effect on GDP over the years are (1) improvements in capital and labour productivity (2) energy efficiency and (3) the cap on carbon emissions and (4) climate change effects in the form of temperature increase decreasing labour productivity.

When comparing the four openENTRANCE scenarios to the reference scenario, it is found that the GDP across the four openENTRANCE scenarios are similar to the reference scenario and results are robust between the two macro-economic models. Specifically, GDP deviates in the openENTRANCE scenarios at most by 1% from the reference scenario in 2050. A lower GDP is mostly due to the stricter carbon cap in the openENTRANCE scenarios compared to the reference scenario and a higher GDP results from the assumption on increased energy efficiency in those scenarios.

GDP is often used as a measure of a country's economic health. It can be calculated in three different ways. Under the expenditure approach, it is the sum of expenditures by households and governments, investments and inventories. Under the income approach, it is the sum of all income earned by households, governments and investors. Under the production approach, it is the total production value, minus the costs spend on intermediate goods. Note that all three approaches result in exactly the same level of GDP.

Figure 3-1 gives the trend in Gross Domestic Product (GDP) for the EU for all scenarios. The black dashed line illustrates GDP in the reference scenario. For this scenario, both models have been calibrated such that growth in GDP follows the exact GDP trend in the EU reference scenario between 2020 and 2050 (Capros et al., 2016). The slight difference between EXIOMOD and REMES-EU and the reference scenario is because REMES-EU does not consider Croatia in its data, and that the calibration is made on a per-country basis.

The results indicate that openENTRANCE scenarios have a mildly negative effect on GDP in both Gradual Development and Societal Commitment scenarios. This is not surprising since the carbon cap has such a negative effect on the economy. Namely, the cap on carbon is an extra restriction on production processes. Initially, firms try to keep the levels of production equal to the situation without a cap by switching to cleaner energy sources. However, when the cap is getting stricter in later years, the other way to reduce CO2 emissions is by reducing the production levels which in turn has a decreasing effect on GDP.

On the other hand, the Techno-Friendly and the Directed transition scenario perform similarly or even better than the reference scenario thanks to the improvements in technology that take place under these scenarios. This effect dominates the negative effect of the cap on carbon. Table 3-1 shows that GDP deviates at most 1.0% from the reference scenario in 2050 for both models. Also, for all scenarios, the two models produce fairly similar results in terms of deviations from the reference scenario.

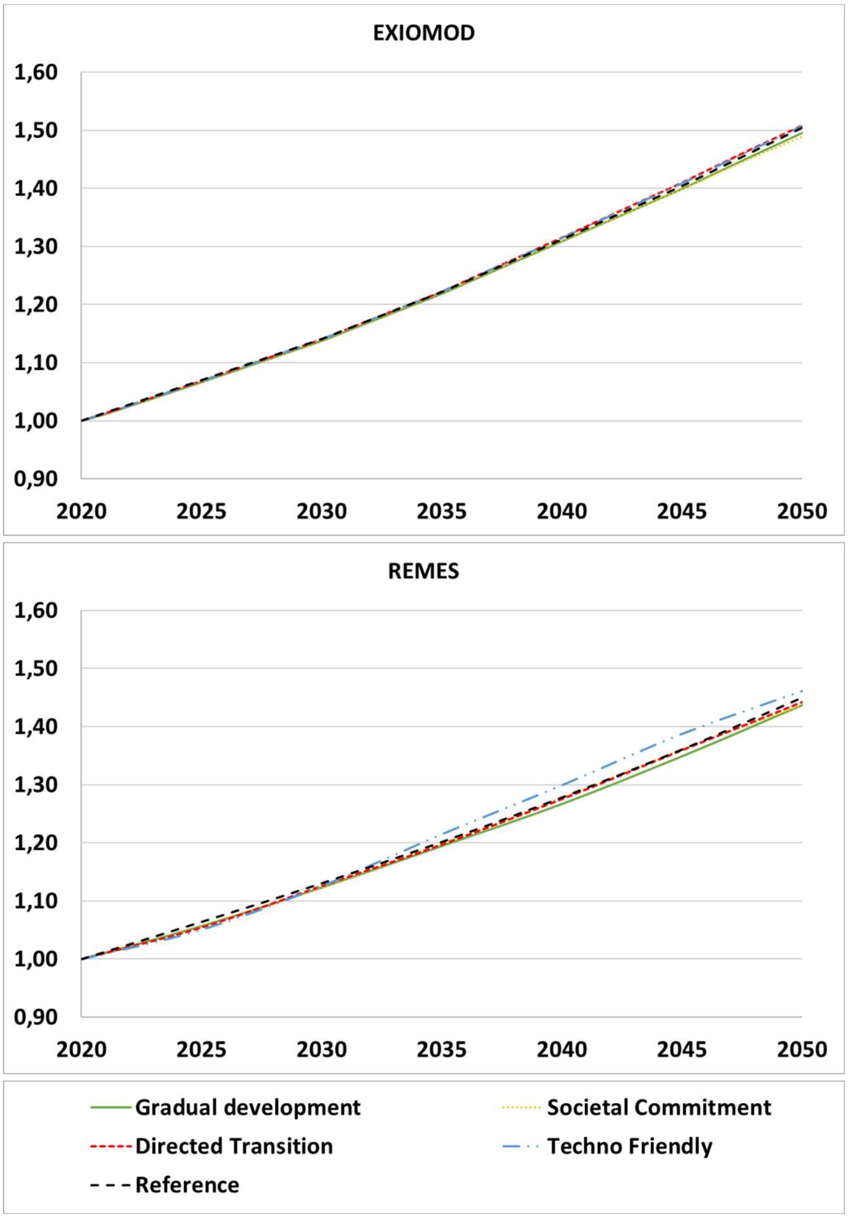


Figure 3-1: Index of Gross Domestic Product for four openENTRANCE scenarios and the reference scenario between 2020 and 2050. Results for EXIOMOD are given in the top panel, results for REMES-EU in the bottom panel.

When computing the macro-economic impact of the energy transition scenarios on GDP, both models find that Techno Friendly and Directed transition have the most positive effect on GDP. Besides, the results are robust across the two models as is shown in Table 3-1.

Table 3-1: Percentage difference in GDP with the reference Scenario in 2050.

Scenario	EXIOMOD	REMES-EU
Reference	0,0%	0.0%
Gradual Development	-0.6%	-0.9%
Societal Commitment	-1.0%	-0.9%
Directed Transition	0.2%	-0.6%
Techno Friendly	0.1%	0.8%

The scenario elements that have the greatest effect on GDP are (1) improvements in capital and labour productivity – or technological progress – which are the main driver of an increase in GDP (2) the tightening cap on carbon emissions has a slight decreasing effect on GDP, (3) the energy efficiency measures have a slight increasing effect on GDP and (4) temperature increases result in lower labour productivity and thus a lower GDP especially in the reference scenario[3]. Technological progress is part of the reference scenario as well as the four openENTRANCE scenarios, therefore the main upwards trend is seen in all scenarios. The more technology-based scenarios, Techno-Friendly and Directed transition, have the highest expected GDP in 2050. This result is derived from the assumption on energy efficiency which is large enough to offset the negative economic effects from the strict carbon cap.

In addition, due to their implementation differences, the two macro-economic models might show different weights for the impact of the same scenario element on GDP, albeit the direction of the GDP variation is the same across models (see Table 3-2).

[3] Changes in the economy have an effect on the climate (e.g. increases in CO2 emissions will increase global temperature) and vice versa, i.e. climate effects impacts on the economy. If our production processes do not change, temperatures will continue to increase over the next decades. Regions where temperatures are already high in summer are expected to see higher incidences of negative impacts in labour productivity (Watkiss et al, 2019). High temperatures degrade the working conditions for employees who do not have access to air conditioning. It changes the mood of individuals and can result in physical effects like difficulty of breathing and exhaustion (Yildirim et al., 2009). Watkiss et al, 2019 show that there is an optimal temperature for working in the industrial and construction sector of 10.8°C and 10°C respectively. Workers become less productive in temperatures higher or lower than this temperature. By taking the average temperatures for each country in the EU, the parabolic labour productivity response-curve with respect to temperatures from Watkiss et al, 2019 and expected temperature increases under the different scenarios, the effect of climate change effect on labour productivity has been included in the four openENTRANCE scenarios and the reference scenario. For the expected temperature increases in year 2050, the trajectories from Figure 7.1 from Hof et al., 2011 have been assumed under the business-as-usual, the 2°C and 1.5°C increase scenario.

Table 3-2: Which elements of the scenarios are responsible for an increase or decrease in GDP when compared to the base year of the model.

Scenario	EXIOMOD	REMES-EU
Growth in population and technological progress	Strong increasing effect	Strong increasing effect
Electricity mix	No or little effect	Slight increasing Effect
Energy Efficiency	Increasing effect	Increasing Effect
Shift in Household spending (GENeSYS-MOD inputs)	No or little effect	Increasing Effect
Carbon Cap	decreasing effect	Strong decreasing effect
Circular economy (servitization)	No or little effect	Slight decreasing effect
Shift in energy input (GENeSYS-MOD inputs)	No or little effect	Increasing effect
Shift from gas to hydrogen	No or little effect	-

3.2 Economic output per sector

Box 3.2: Summary of results on economic output per sector

The two models produce fairly similar results in terms of effects on sectoral output. In the reference scenario, growth in fossil-based energy sectors is expected to be limited or even decreasing. Other non-energy sectors, like manufacturing, service, and aluminum and transport are expected to follow a growth between 40-60% between 2020 and 2050. In EXIOMOD, the electricity sector is increasing quite rapidly in the reference scenario already because it includes an extra technology change assumption which REMES-EU does not include.

The openENTRANCE scenarios show a large increase in activity in the hydrogen sector, (renewable) electricity sector(s), and the service sector. The service sector increases because of the shift to a circular economy which replaces the old business model of owning a product with a leasing service. Hydrogen and electricity are clean energy alternatives (e.g. the use of these energy types result in less CO2 emissions compared to the use of fossil-based energy sources), which explains the increase in productivity of the sectors that produce these two types of energy.

Sectoral output is either defined as the value of output sold to other agents which is equal to sum of spending on intermediate use, capital costs, labour costs, profits and taxes minus subsidies. By looking at the size of sectoral output, one can signal which sectors are dominant in the European economy. Both models use EXIOBASE as underlying database, therefore sectoral output is defined in millions of euros and consistent across the models.

For forecasting the sectoral output until 2050, output can be measured using the 'value' or 'volume' definition. The 'value' definition accounts for the evolution of prices whereas the 'volume' definition excludes it by freezing the price levels at the base year. For the base year, for which the model has been calibrated, all price indices are equal to one. Therefore, the two definitions result in the same monetary outcomes. The figures in this section present results expressed in 'volume'. When sectoral output is presented in 'value' definition, we can only motivate that more (or less) money is flowing through a sector, but we have no information what this means in terms of quantities sold. The latter is what we are mostly interested in, this gives information to which sectors the focus of the economy is shifting.

Figure 3-2 gives sectoral output for the reference scenario. This scenario only includes a couple of assumptions (see Table 2-7). Namely, technological progress, measured as Total Factor Productivity, which constitutes the main driver of an increase in GDP, energy efficiency, and a carbon cap set to achieve a 40% reduction of CO2 emissions relative to 2007. In addition, EXIOMOD assumes that the electricity mix (e.g. the production shares of electricity coming from wind solar, gas, coal etc) is taken exogenously from GENeSYS-MOD. The database underlying to EXIOMOD has separate electricity sectors defined by each technology producing electricity. REMES-EU contains only one electricity sector where electricity is produced by a mix of the technologies (e.g. wind, solar, coal etc). Figure 3-2 shows that the models produce fairly similar results. Both models show the same six sectors with relatively high growth (40-60% with respect to 2020): manufacturing, service, agriculture, aluminium production, transport, and trade and distribution of electricity and gas. These sectors are least affected by the energy efficiency assumption or the modest cap on carbon emissions. In fact, they are mostly benefiting from the improved capital and labour productivity, since they follow the same growth as GDP (see Figure 3-1).

Similarities between the two models are also visible for three energy producing sectors, i.e. the modest growth rate of the production of hydrogen[4], natural gas and crude oil and coal extraction for both models. The reference scenario includes a carbon cap, which hampers the growth of fossil-based energy sectors like natural gas, crude oil and coal extraction. Also, the energy efficiency measures in other sectors imply a reduction in demand of (fossil-based) energy products. This further hampers the growth of these three sectors.

Differences in results for the two models are seen for the electricity sector and the coal extraction sector. This difference arises from one extra assumption that EXIOMOD has in the reference scenario, namely the extra exogenous electricity technology mix assumption in the reference scenario that is similar to what is implemented in the Gradual Development scenario. This technology mix is taken exogenously from GENeSYS-MOD, where less electricity is produced using coals as input, and more electricity is produced using clean technologies like wind and solar. Therefore, demand for coal decreases more heavily in the reference scenario when output is produced by EXIOMOD. Demand for

[4] Note that Figure 3-2 gives the index of sectoral output in *the reference scenario*. This scenario does not have a very strict cap. Therefore, in REMES-EU, the production of hydrogen does not yet increase fast in this scenario. Under EXIOMOD, the product 'gas' can be produced by two different sectors, the natural gas sector and the hydrogen sector. The production shares are exogenously taken from GENeSYS-MOD for the four decarbonization scenarios, but are not yet implemented in the reference scenario.

electricity increases due to the combination of (1) a carbon cap which forces the model to choose for cleaner production of energy (2) electricity that becomes cleaner over the years due to the exogenous technology mix assumption. REMES-EU, on the other hand, only assumes one electricity sector and the technology mix is endogenously determined by the model.

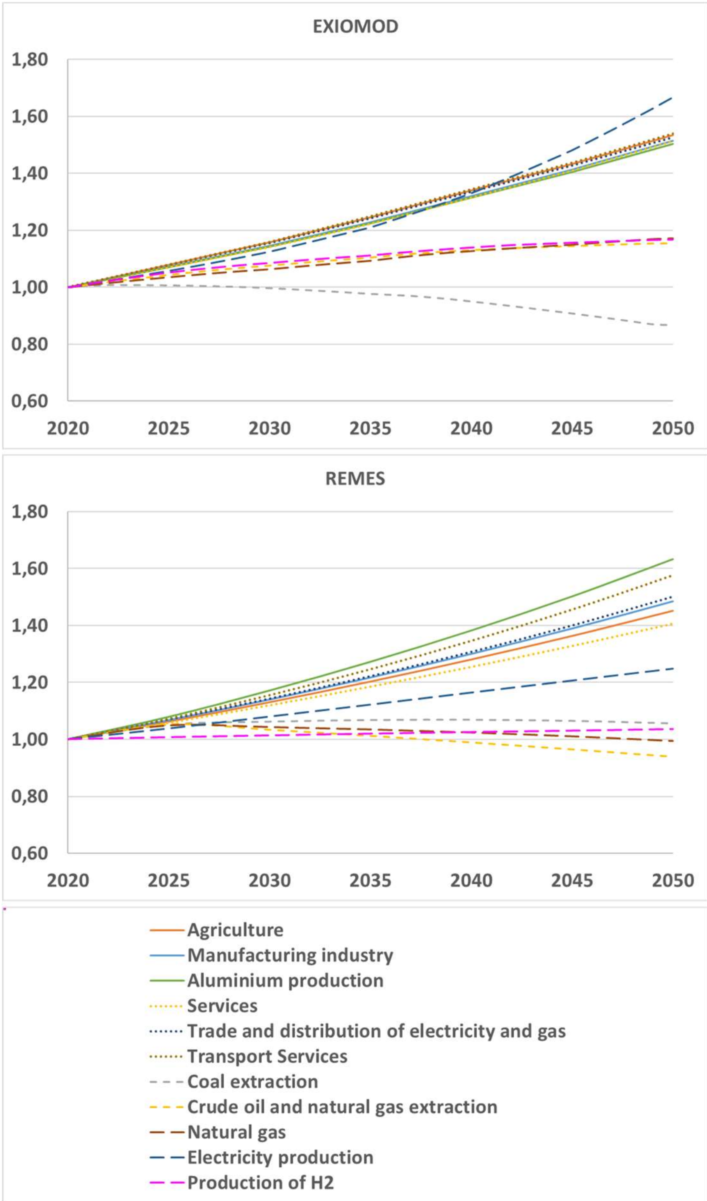


Figure 3-2: Index of sectoral output on EU level for the Reference scenario between 2020 and 2050. Results for EXIOMOD are given in the top panel, results for REMES-EU in the bottom panel.

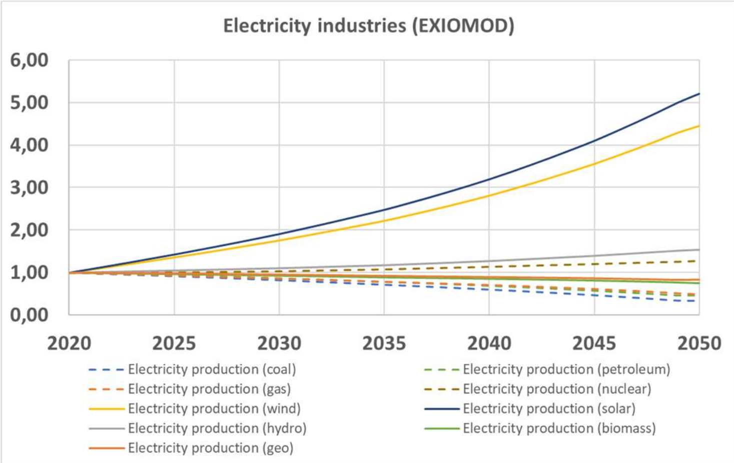


Figure 3-3: Index of sectoral output of electricity sectors on EU level for the Reference scenario between 2020 and 2050.

EXIOMOD uses database EXIOBASE that defines nine different sectors that produce electricity. Figure 3-3 illustrates expected growth or decline of electricity producing sectors in the reference scenario with respect to year 2020. This result is driven mostly by the exogenous electricity mix assumption. For the reference scenario this is assumed to be equal to the electricity mix of Gradual Development and is taken from the GENeSYS-MOD trajectories. As expected, clean electricity mix technologies like electricity from wind and solar and hydro are increasing.

Table 3-3: Percentage change of total output for four openENTRANCE scenarios with respect to the reference scenario in 2050 for EU27 and ten sectors.

	EXIOMOD					REMES-EU			
Scenario: Sectors:	GD	SC	DT	TF		GD	SC	DT	TF
Agriculture	-4%	-10%	-6%	-3%		-6%	-17%	-11%	-6%
Coal extraction	-54%	-62%	-63%	-62%		-34%	-52%	-46%	-58%
Crude oil and natural gas extraction	-44%	-77%	-76%	-76%		-62%	-74%	-73%	-81%
Manufacturing industry	-5%	-13%	-8%	-3%		-7%	-17%	-12%	-2%
Aluminium production	-13%	-34%	-22%	-6%		-11%	-32%	-21%	-12%
Trade and distribution of electricity and gas	-4%	-9%	-3%	-3%		0%	-1%	1%	-0%
Natural gas	-72%	-86%	-85%	-80%		-31%	-59%	-57%	-73%
Services	3%	9%	6%	2%		3%	10%	6%	2%
Transport Services	-6%	-16%	-12%	-8%		-6%	-7%	-5%	3%
Electricity production	57%	65%	57%	44%		68%	84%	102%	81%

The figures in this section show the expected sectoral growth trajectories for the reference scenario. The other four scenarios have more ambitious climate targets. Gradual Development (GD) aims at limiting global warming to 2 degrees Celsius, whereas Societal Commitment (SC), Directed Transition (DT) and Techno friendly (TF) aim limiting global warming to at most 1.5 degrees Celsius compared to pre-industrial levels.

Comparing the effects of these more ambitious targets on the growth on European sectors (see Table 3-3), it is found that almost all sectors are expected to face lower growth compared to the reference situation in 2050. There are two exceptions, i.e. the sectors that produce electricity, and the service sector.

The increase in demand for electricity is on the one hand exogenously implemented in the models via changing the use of energy products in manufacturing, service, transport sectors and households (i.e. exogenous input from GENeSYS-MOD scenarios). On the other hand, the shift from producing hydrogen instead of natural gas causes an increase in electricity production. The hydrogen sector has a high electricity use. An extra effect – that only takes place in REMES-EU – is that the introduction of a hydrogen sector also *reduces* the amount of electricity consumed. Namely, manufacturing sectors can substitute electricity by hydrogen as a possible energy source based on the external technology shift provided by the energy system model. Moreover, hydrogen can be produced using Steam Reformation, which does not require as much electricity as electrolysis, which contributes to the reduced growth of electricity demand.

The service sector is also growing in size due to the servitization assumption. That is, it is assumed that households gradually shift from owning to leasing goods. Leasing and repair services are products of the service sector. These products replaces the old business model in which consumers consume only new products and materials, which are produced by the manufacturing sector. Especially in scenario 'Societal Commitment', society is motivated to move towards circular business models, which is shown by an extra high increase of the service sector, and a relatively large decrease of the manufacturing sector with respect to the reference in 2050.

Results are robust across the two models, specifically with regard to the direction and magnitudes of growth (or decline) with respect to the reference scenario in 2050. There is one sector where the differences between the two models are more obvious, which is the sector that produces natural gas. For scenario GD, SC, and DT, the relative decrease in this sector with respect to the reference scenario in 2050 is much more modest for REMES-EU compared to what was computed by EXIOMOD. This result is driven by the REMES-EU assumption for some scenarios that hydrogen production is partly covered by steam reformation using natural gas with carbon capture and storage. This, coupled with the effect of improvements in carbon efficiency leads to a slower decrease in the use of natural gas when compared to the EXIOMOD results.

We have excluded the hydrogen sector from the table, because the production of hydrogen is nearly zero in the base years of the models and the uptake of hydrogen is assumed not to be part of the reference scenario. Therefore, under the reference scenario the hydrogen sector is negligible. The decarbonisation scenarios assume a large uptake of hydrogen, which results in that the hydrogen sector under decarbonisation scenarios is thousands of times larger than under the reference scenario.

3.3 Electricity demand

Box 3.3: Summary of results on electricity demand

Demand for electricity is expected to increase fast under the openENTRANCE scenarios, this result is robust across the two models. Scenario Directed Transition and Societal Commitment show the highest increase in electricity demand. EXIOMOD shows a faster increase in electricity demand compared to REMES-EU. This difference can be explained by the differing scenario assumptions in each model and by the differences in dynamics and equations that form each model. For example, in REMES-EU, hydrogen is a good substitute for electricity, while under EXIOMOD the product 'gas' can be produced by the hydrogen sector and the natural gas sector. The production share of these two sectors is taken from GENeSYS-MOD, which makes the mixed-product 'gas' a less clean substitute for electricity.

Demand of electricity is defined as demand from industries, households and governments. Figure 3-4 gives the trend in electricity demand from 2020 to 2050. Under all scenarios the demand of electricity is expected to increase, this result is robust across the two models. Scenarios Directed Transition and Societal Commitment result in the largest increase in electricity demand. The scenario assumptions that are most responsible for this are (1) the increased use of electricity in manufacturing, service and transport sectors and households, taken from GENeSYS-MOD (2) the cap on carbon that forces industries to shift to cleaner energy sources that result in less CO2 emissions.

We can conclude that the effect of the decarbonisation scenarios on the demand for electricity is robust across the two models, still there are some differences when results are compared across the two models that we like to explain:

- The increase in demand for electricity is larger when the scenarios are computed using EXIOMOD compared to when computed using REMES-EU. The difference can be explained via the difference in how the scenarios are implemented in the two models. REMES-EU assumes that sectors that implement energy use from GENeSYS-MOD (i.e. manufacturing, service and transport) have energy elasticity that are very small. In other words, these sectors fix energy use to what was output of GENeSYS-mod and are very inflexible in adjusting their energy use to the needs of the carbon cap. EXIOMOD on the other hand keeps the energy elasticities relatively high, which allows the sector to adjust the use of energy such that the carbon cap can be more easily reached. This might therefore result in an even higher demand of electricity (the clean alternative) compared to what was initially input of GENeSYS-MOD.
- The trajectory from 2020 to 2050 differs for the two models, this difference can be explained by the way in which the two models process external technology data. For EXIOMOD, the difference is partially explained by the smoothing of trajectories of certain inputs between 2020 and 2050 to improve the solvability of the model. Especially output trajectories of GENeSYS-MOD, that serve as input to the macro-economic models, are fluctuating. GENeSYS-MOD provides data on the use of energy types by the manufacturing industry, services sector and transport, sector. When changes in industries' energy use are too large compared to the energy use of the year before, the model has a hard time finding an equilibrium solution. REMES-EU implements GENeSYS-MOD scenarios for 5-year intervals.
- In addition, results of REMES-EU also show that electricity demand experiences a change in direction, generally after 2035. This coincides with the large scale kick-in of the hydrogen sector, which starts competing with electricity in some sectors, as an energy carrier. This dimple in electricity demand is not shown when the scenarios are computed using EXIOMOD because the hydrogen sector is implemented in the model in a different manner compared to REMES-EU. Namely, there is only one product 'gas' that is either produced by the natural gas sector or by the hydrogen sector. The production share between these two sectors is exogenously taken from GENeSYS-MOD (see Section 2.2.3 for the differences in hydrogen production in the two models).

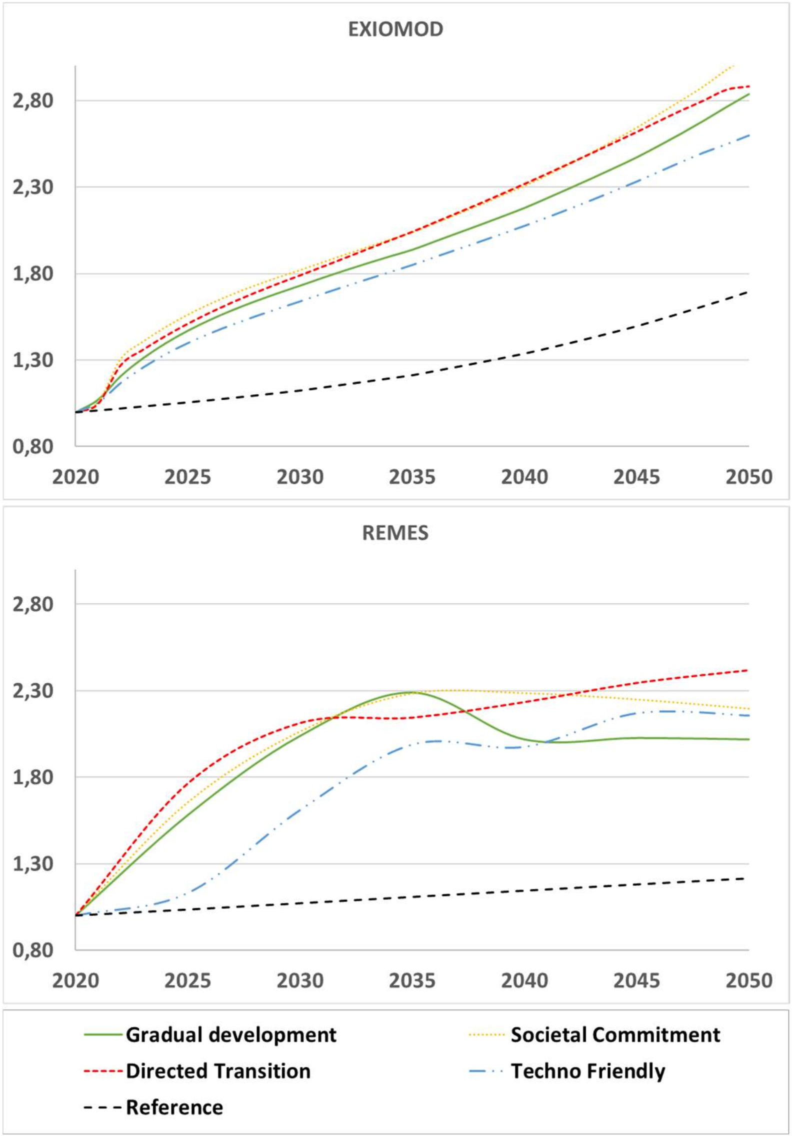


Figure 3-4: Index of electricity demand on EU level for the reference scenario between 2020 and 2050. Results for EXIOMOD are given in the top panel, results for REMES-EU in the bottom panel.

3.4 Fuel demand

Box 3.4: Summary of results on fuel demand

The results of both models show that demand for fuels is expected to decrease for each openENTRANCE scenario. The carbon cap forces the models to shift to energy products that produce less emissions (e.g. electricity and hydrogen). Demand for fossil-based energy types (e.g. gasoline, diesel, crude oil, natural gas) therefore declines. Also, GENeSYS-MOD scenario inputs exogenously force the manufacturing industry, services and transport to shift towards cleaner energy sources.

Demand for fuels equals demand from the production sectors plus demand from households, government and investors. Figure 3-5 gives the trend in fuel demand from 2020 to 2050. Fuel types are the aggregate of crude oil, gasoline, diesel, heavy distillate, natural gas, coal, and biofuels.

It is clear from the figures that both models find a decrease in consumption for fossil fuels due to (1) the reduction of the CO2 cap, which penalizes the usage of polluting energy sources (2) the GENeSYS-MOD input that shifts demand for energy in a selection of industries (i.e. manufacturing, transport and service sector) to cleaner energy sources like electricity and hydrogen.

As expected, REMES-EU projects a slightly stronger reduction of the use of fossil fuels, compared to EXIOMOD. This boils down to the fact that the two models use different underlying databases for the economic analysis (e.g. different way in which initial CO2 emissions are distributed over the use of fuels by sectors), different modelling of the trade with the extra-European countries as well as handle differently the external data provided by the energy system model GENeSYS-MOD. It is interesting to notice that the two models, albeit prescribing a similar decrease in consumption of fossil fuels towards 2050

, display a different pathway on the way those consumption levels are decreased over time. While REMES-EU displays a sharp decrease in consumption already starting after 2020, EXIOMOD prescribes a more gradual decrease over time. The two models integrate the external dataset related to the change in energy mix using different elasticities of substitution, mostly due to cope with computational issues. Moreover, the two models consider different ways to include CO2 emissions control, with EXIOMOD introducing a tax on the production side, while REMES-EU introducing the need for purchase CO2 allowances alongside the consumption of fossil fuels. These differences contribute in defining different paths for the two models to project the reduction in consumption of fossil fuels.

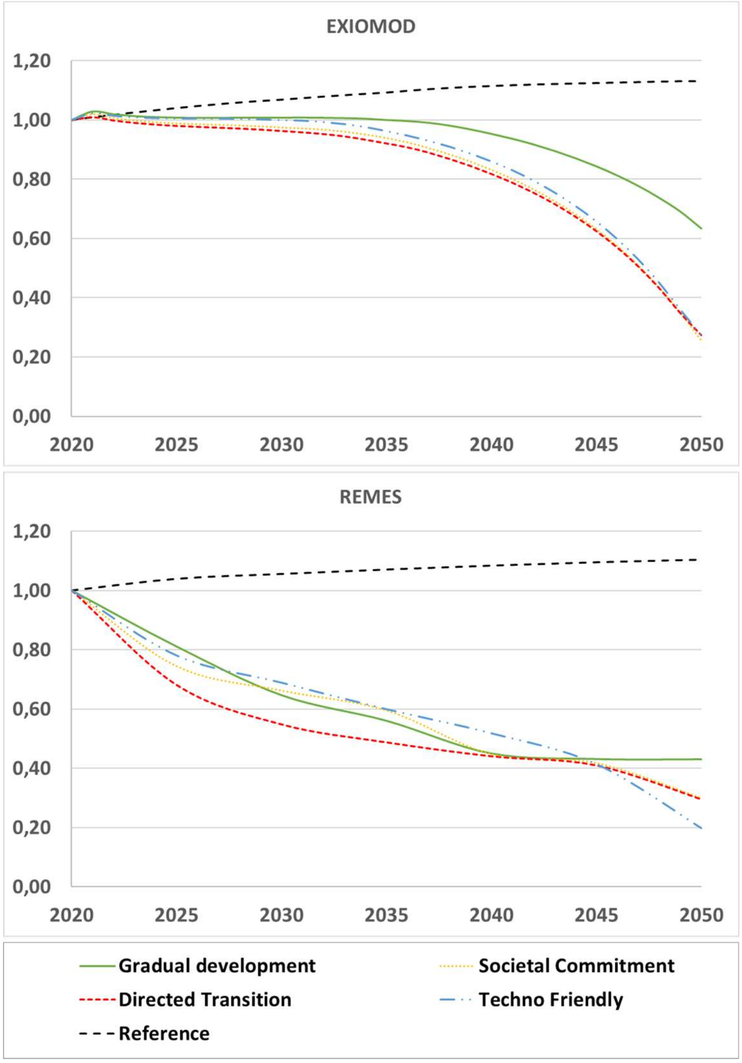


Figure 3-5: Index of fuel demand on EU level for the reference scenario between 2020 and 2050. Results for EXIOMOD are given in the top panel, results for REMES-EU in the bottom panel.

3.5 Final consumption

Box 3.5: Summary of results on final consumption

Final consumption consists of demand from households and Governments. Both models show that demand for fossil-based energy sources decrease when openENTRANCE scenarios are compared to the reference scenario.

The two models show different results for the effect of demand on electricity. REMES-EU shows that all decarbonization scenarios increase in demand for electricity, EXIOMOD shows smaller increases and for some scenarios decrease in the demand of electricity when compared to the reference scenario. This EXIOMOD result is due to the fact that households do not need to substitute one energy product by another cleaner energy product – contrary to the situation in industries. Instead, households choose to spend their money on other products (e.g. services, consumer products) with low emissions where prices are lower than the electricity price.

The two models also show different results when comparing total demand for services and manufactured products. In REMES-EU, the higher price for services (due to the servitization measure in industries) results in a lower demand for service product by households and governments. In EXIOMOD, the higher price of services is still a lower price than the price of electricity, and thereby an attractive product to spend its money on.

Final consumption is defined as the sum of government consumption and household consumption. Table 3-4 gives the percentage changes in final consumption in 2050 in the decarbonisation scenarios with respect to the reference scenario. In general, the two models show a large decrease in the use of fossil energy products and demand for other products remain relatively stable compared to the situation in the reference scenario in 2050.

Fossil fuels and electricity (see Table 3-4).

The decrease in demand for fossil fuels can easily be explained. Due to a strict cap on carbon in the four openENTRANCE scenarios, the use of energy products with high CO2 emissions are penalized and thereby less attractive for households and governments.

The effects on the demand for electricity is different for EXIOMOD compared to REMES-EU. There are two explanations behind this difference. First, there is a difference in the modelling of behaviour in the two models. EXIOMOD results indicate that a carbon cap increases prices of electricity in the whole economy, and thereby also for households and governments. This makes electricity a less favourable product compared to other lower-emission products that the consumer can purchase. Where industries require energy to produce, no minimum energy consumption is assumed for households and governments. This difference in behaviour explains why industries still buy electricity against a high price (because it is still the most environmental friendly option out of the different energy types), households simply decide to decrease its total amount of energy use. In other words, production sectors have are more inelastic when it comes to reallocate their expenditure compared to households. Second, EXIOMOD takes the exogenous household energy shares from GENeSYS-MOD. For example, these shares tell households in EXIOMOD to spend 20% of their energy demand on gasoline, 20% on diesel, and 60% on electricity. In general, these household energy shares favour the use of electricity over other the use of other energy types. Then why is the electricity demand in the Techno-Friendly scenario lower than in the reference scenario? That is because the GENeSYS-MOD electricity demand for household does not show an increase between 2020 and 2050, where it is increasing in the reference scenario, which is likely due to improvements in energy efficiency. REMES-EU does not take exogenous data from GENeSYS-MOD defining the energy consumption of households.

The large decreases in demand for fuels gives the incorrect impression that household and government budgets are drastically lower compared to the reference scenario. For EXIOMOD, there only seems to be a small increase in demand for services. However, this is a very large sector. A small relative increase with respect to the reference scenario in 2050 still implies a large absolute increase in spending on this product.

Manufacturing products and services (see Table 3-4).

REMES-EU shows that household and government demand for services is decreasing and for manufacturing goods are increasing, EXIOMOD shows the opposite result. This can be explained as follows. Both models implement the shift from manufactured goods to services only in the industrial sectors. For REMES-EU, the large increase in purchase of services from the production sectors leads to increasing prices for services. This, in turn, leads to a decrease in demand from the final consumers. The opposite happens with manufactured goods, whose final demand increases in REMES-EU. Using EXIOMOD, both prices of manufactured goods and services increase slightly. However, this slight price increase is still smaller than the price increase for electricity for example. Household and governments thereby shift consumption to products with low CO2 emissions and a relatively low price.

This result is however sensitive to the assumption that servitization and promotion of repair services is only implemented in industrial sectors. In further research, the servitization assumption should be extended to households, which would result in more realistic results for households.

Table 3-4: Percentage change of final consumption for four openENTRANCE scenario with respect to the reference scenario in 2050 for EU27 and seventeen commodities.

	EXIOMOD					REMES-EU			
Scenario: Sectors:	GD	SC	DT	TF		GD	SC	DT	TF
Agriculture	-1 %	-3 %	-2 %	-2 %		-1 %	0 %	-1 %	-2 %
Manufactory	0 %	-2 %	-1 %	-1 %		2 %	9 %	5 %	5 %
Aluminium	-1 %	-3 %	-1 %	-2 %		3 %	13 %	5 %	7 %
Services	1 %	3 %	3 %	4 %		-3 %	-7 %	1 %	-4 %
Transport services	-3 %	-12 %	-6 %	-3 %		-4 %	0 %	4 %	-1 %
Electricity	-8 %	25 %	61 %	-17 %		68 %	123 %	121 %	177 %
Trade and distribution services of electricity	-3 %	-12 %	1 %	-1 %		-4 %	-4 %	-7 %	-2 %
Steam and hot water	-4 %	-17 %	-16 %	-17 %		62 %	65 %	97 %	92 %
Crude Oil	-94 %	-97 %	-97 %	-97 %		-77 %	-82 %	-86 %	-81 %
Gasoline	-41 %	-80 %	-77 %	-81 %		-96 %	-97 %	-98 %	-97 %
Diesel	-39 %	-79 %	-75 %	-78 %		-93 %	-97 %	-98 %	-96 %
Heavy distillate	-51 %	-85 %	-76 %	-82 %		-87 %	-92 %	-95 %	-91 %
Natural gas	-38 %	-83 %	-89 %	-75 %		-73 %	-85 %	-88 %	-87 %
Coal	-97 %	-99 %	-99 %	-99 %		-93 %	-98 %	-99 %	-98 %
Biofuels	33 %	-41 %	-21 %	-50 %		-4 %	-9 %	17 %	18 %
Other fuels	-45 %	-79 %	-79 %	-80 %		-66 %	-87 %	-94 %	-85 %

3.6 CO2 emissions

Box 3.6: Summary of results on CO2 emissions

CO2 emissions are decreasing over the years. This decrease is caused by (1) the cap on CO2 emissions, (2) improved carbon efficiency (3) energy efficiency and (4) exogenous energy shares from GENeSYS-MOD that force industries to use more electricity and less fossil fuels (5) taxes on the use of fossil fuels and subsidies on the use of electricity.

The cap on CO2 is one of the biggest drivers of the CO2 reduction between 2020 and 2050. Still, between 2020 and 2030 the cap on CO2 is not for all regions binding, i.e. CO2 emissions can be even lower than the cap on CO2 due to the other measures. After 2040 the yearly allowed CO2 emissions are such low that a positive CO2 price is needed to keep the emissions below the CO2 cap.

Figure 3-6 shows CO2 emissions for the reference scenario. Emissions are expressed in million tons and are benchmarked with their historical pattern from Eurostat[5]. For the reference scenario it is assumed that emissions reduce with 40% with respect to 1990 (e.g. the base year of REMES-EU).

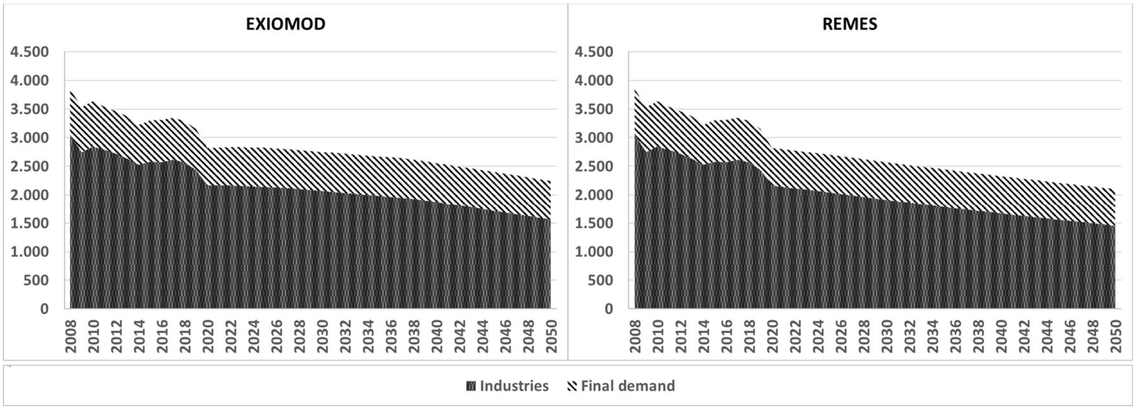


Figure 3-6: Total CO2 emissions in million tons for the reference scenario between 2008 and 2050, differentiated by industries and final demand. Data between 2008-2020 is based on historic trajectories from Eurostat. Results for EXIOMOD are given in the left panel, results for REMES-EU in the right panel.

In order to reach the climate targets as prescribed in the four openENTRANCE scenarios, CO2 emissions need to have a larger decrease than what is visualized in the reference scenario in Figure 3-6. The Gradual Development scenario is the mildest of the openENTRANCE scenarios regarding the emissions reduction. Limiting temperature increase to at most 2 degrees increase Celsius is assumed to be reached when CO2 emissions are reduced by 88% in 2050 with respect to the 1990 levels. This reduction is forced via the CO2 cap. The gradual development scenario is presented in Figure 3-7 as a green continuous line.

The other three scenarios result in an even larger reduction in CO2 emissions, since these scenarios claim to result in an at most 1.5 degrees Celsius increase in temperature. This corresponds to a CO2-cap equal to 92% reduction of emissions with respect to 1990 levels (EXIOMOD)[6] and 97% reduction of emission with respect to 1990 levels (REMES-EU).

The economy is able to reach the CO2 trajectories as presented in Figure 3-7 because it diminished its use of fossil fuels and substitute these for cleaner energy products. A positive price on carbon is

[5] Total CO2 emissions from household, government and industries do not exactly add up to what has historically been reported by national bureau of statistics. Therefore, for the base years of the models, the emissions are calibrated to the official reported levels.

[6] The cap in EXIOMOD could not decrease further than a 92% reduction with respect to the level in 2007. A further decrease of CO2 allowances does not result in an optimal solution.

necessary to motivate industries to reduce CO2 emissions and make changes in the production processes. Between 2020 and 2030 the cap on CO2 is not for all regions and scenarios binding, i.e. CO2 emissions can be even lower than the cap on CO2 due to the other measures. After 2040 the yearly allowed CO2 emissions are such low that a positive CO2 price is needed to keep the emissions below the CO2 cap.

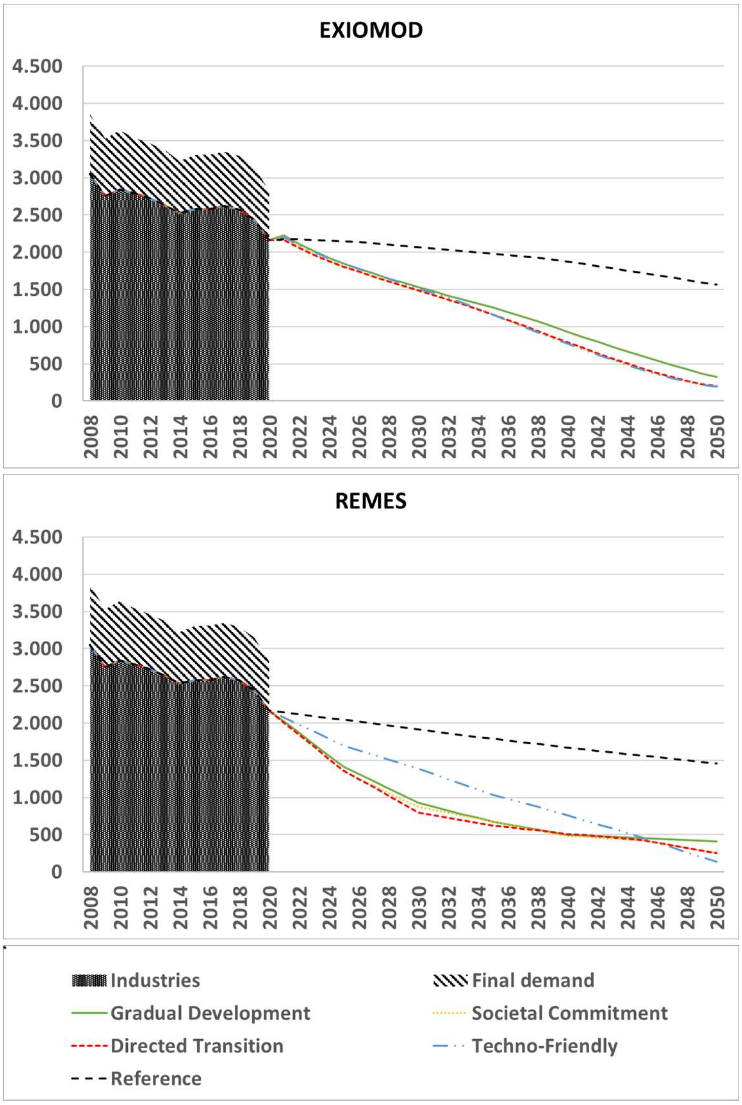


Figure 3-7: Total CO2 emissions in million tons for the reference scenario and four openENTRANCE scenarios between 2008 and 2050. Data between 2008-2020 is based on historic trajectories from Eurostat. Results for EXIOMOD are given in the top panel, results for REMES-EU in the bottom panel.

3.7 CO2 price

Box 3.7: Summary of results on CO2 price

When the carbon cap becomes strict, countries need a positive CO2 price as driver to keep emissions lower than the CO2 cap. Both models show that as of 2045, the price of CO2 starts to increase exponentially. The CO2 price found by REMES-EU is much higher than the CO2 price of EXIOMOD, this is due to the different elasticity of substitution assumed by REMES-EU in the energy nest, which does not allow the model to change the energy mix and keeps it strictly as defined by the energy system model. This is showing that the projected pace of the technological change is in line with the policy push provided by CO2 prices up until 2045, after which such push becomes stronger than the pull provided by the technological change and the prices grow faster.

In both models, industries and households need to purchase CO2 allowances in order to emit CO2 emissions. The purchase price of these allowances is called the CO2-price. This price is found by equalizing total demand for emissions (e.g. from industries and households) to total supply of emissions (e.g. the cap on emissions can be seen as the total supply of emissions). When there is a higher demand for emitting CO2 than the cap allows, the CO2-price increases.

This weighted average[7] CO2-price is shown in Figure 3-8 for both models and all scenarios. REMES-EU prescribes a much higher CO2 price under the Techno-Friendly scenario because of its strict decarbonization requirements and the energy mix defined as the one provided externally by GENeSYS-MOD.

The price of CO2 starts to increase exponentially as of 2045. Namely, after 2045 there are very few CO2 allowances left in the economy in the EU. The other measures (energy efficiency, carbon efficiency, subsidies on the use of electricity) are not sufficient anymore to limit the emissions below the cap. Note that it is ‘easier’ to reduce the first 20% of your emissions compared to reducing the last 20% of your emissions and this is visible in the price of CO2.

[7] Each country has to reduce emissions relative to its 1990 levels. Therefore, also each country has its own price on CO2. The weighted average CO2-price is calculated using annual CO2 emissions as weight.

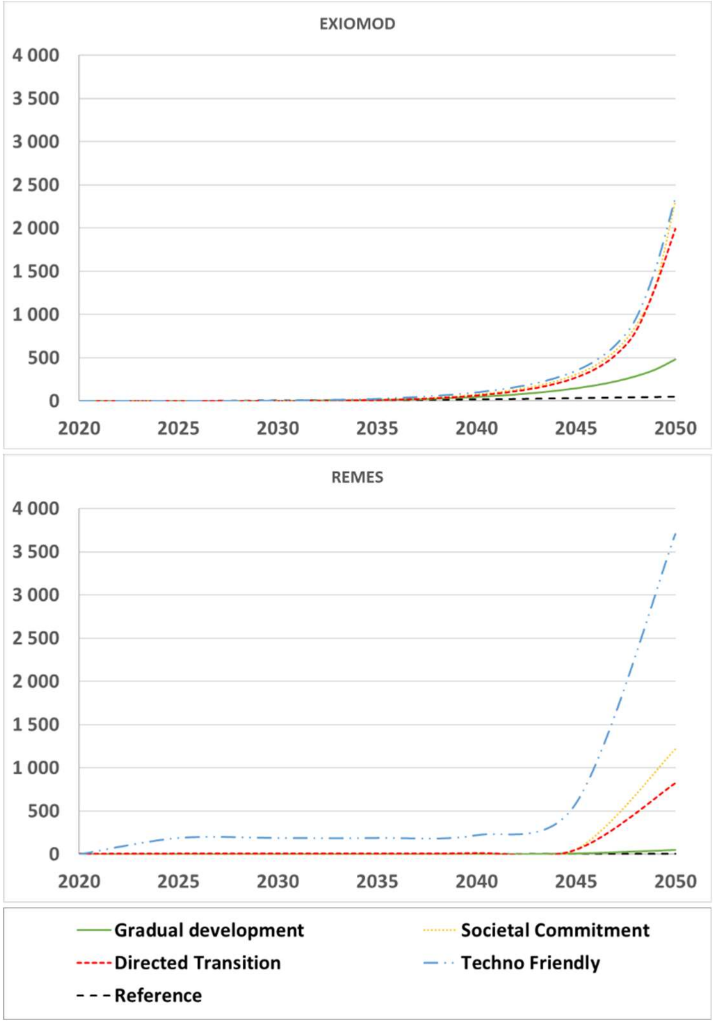


Figure 3-8: The weighted average of CO2 prices of EU countries for four openENTRANCE scenarios and the reference scenario, weight based on CO2 emissions.

3.8 Prices

Box 3.6: Summary of results on price indices

The prices of fossil-fuel products are most affected by the decarbonisation measures.

The differences in the two models become most apparent when comparing the price effects occurring under the different scenarios.

EXIOMOD shows <u>increasing prices</u> of fossil fuels, which are driven by the cap on carbon that becomes stricter towards 2050. The cap on CO2 emissions result in a positive CO2-price which is in turn incorporated in the price of fossil-fuels. The high fossil fuel prices in turn result in decreasing demand for fossil fuels.

In REMES-EU on the other hand, the CO2 allowances are supposed to be purchased alongside fossil fuels in proportion to the amount of emission that a particular fuel produces in a given sector. The increase in CO2 price, due to the lower carbon cap over time, leads to a decrease in demand of fossil fuels which, in turn, <u>leads to a decrease in price</u> of the aforementioned fuels.

Table 3-5: Percentage change of product prices for four openENTRANCE scenarios with respect to the reference scenario in 2050 for EU27 and sixteen commodities. gives the effect of the decarbonisation scenarios on the price levels, when compared to the reference scenario in 2050. Industries that are not as affected by the assumptions in the decarbonisation scenarios show little effect on the price (for example, the agricultural sector), other sectors show a big increase or decrease in price (the sectors that produce fossil fuels).

The differences between the models becomes most apparent when looking at price effects. In general, the comparisons of product prices between the two models show that the direction of the impact (i.e., positive or negative) are almost always opposite when comparing the results of the openENTRANCE scenarios between models. The results for REMES-EU are mostly lower for the openENTRANCE scenarios compared to the reference scenario, while the opposite is true for EXIOMOD.

In EXIOMOD, the much stricter carbon cap in the four openENTRANCE scenarios results in much higher prices of all energy products (crude oil, gasoline, diesel, heavy distillate, natural gas, coal, biofuels and other fuels) and an increase in price of product 'steam and hot water supply' which uses a lot of fossil fuels to produce hot water. This happens because of the penalty for producing polluting commodities is placed on the production through increased costs of production. The extra cost of producing carbon emissions is incorporated in the price of intermediate energy use for each sector. Thus, a higher carbon price results in higher cost of using energy in the production process. The high intermediate price for energy products in turn results in a decrease in demand of energy products by industries. Steam and hot water supply use a lot of fossil fuels in the production proces, the increased production cost are incorporated in the price for this product.

In REMES-EU, CO2 allowances are modelled as a commodity that is purchased alongside fossil fuels in proportion to the amount of emissions the particular fuel produces in a given sector. The penalty for the usage of polluting commodities is modelled on the demand side, where the total amount of CO2 allowances available in the economy are defined by the so-called carbon cap. As the carbon cap is decreased over time the price of the CO2 allowances will increase due to the diminished supply availability. The increase in CO2 price due to the lower carbon cap over time, leads to a decrease in demand for CO2 allowances. The decrease in demand of CO2 allowances in turn leads to a decrease in demand of the related fossil fuel, since such commodities are considered as complementary. Finally, the decrease in demand of fossil fuels leads to a decrease in price of the aforementioned fuels.

Table 3-5: Percentage change of product prices for four openENTRANCE scenarios with respect to the reference scenario in 2050 for EU27 and sixteen commodities.

	EXIOMOD					REMES-EU			
Sector	GD	SC	DT	TF		GD	SC	DT	TF
Agriculture	-3 %	-14 %	-14 %	-14 %		1 %	0 %	4 %	9 %
Manufacturing industry	1 %	5 %	5 %	6 %		-5 %	-8 %	-4 %	1 %
Aluminium production	0 %	2 %	2 %	3 %		-7 %	-12 %	-4 %	0 %
Services	-3 %	-11 %	-12 %	-11 %		4 %	7 %	13 %	7 %
Transport services	42 %	191 %	166 %	134 %		1 %	-1 %	22 %	18 %
Electricity	8 %	23 %	21 %	36 %		11 %	7 %	11 %	16 %
Trade and distribution services of electricity	-1 %	-8 %	-10 %	-10 %		2 %	4 %	2 %	1 %
Steam and hot water supply	206 %	830 %	801 %	809 %		-48 %	-48 %	-43 %	-42 %
Crude Oil	35 %	197 %	196 %	210 %		-5 %	-5 %	8 %	3 %
Gasoline	36 %	198 %	197 %	209 %		-62 %	-62 %	-61 %	-66 %
Diesel	35 %	196 %	195 %	207 %		-31 %	-32 %	-32 %	-41 %
Heavy distillate	34 %	189 %	188 %	200 %		-41 %	-42 %	-38 %	-46 %
Natural gas	31 %	64 %	78 %	90 %		-6 %	-7 %	0 %	-7 %
Coal	54 %	156 %	154 %	171 %		-30 %	-35 %	-32 %	-43 %
Biofuels	-2 %	-10 %	-11 %	-10 %		-60 %	-61 %	-50 %	-48 %
Other fuels	35 %	193 %	191 %	204 %		-60 %	-68 %	-65 %	-72 %

3.9 Simulation of the impacts of the three main drivers on the economy and decarbonization

The openENTRANCE storylines are determined according to the changes of three main drivers: society, technology and policy. One of the main objectives of the economic analyses performed under this project is to simulate how much each of these drivers impact the main macroeconomic indicators. Namely, we focus on determining how much the main shocks[8] relate to societal (behavioral) change, technological change and policy exertion impact on the scenarios where each of these dimensions are predominant. The synthesis of this analysis is shown in the next three subsections (see Table 3-6). The goal is to determine, for each scenario, how much each of these

[8] The decarbonization scenarios consist of a range of measures and assumptions (see Table 2-7 and Appendix C). These measures are implemented as 'shocks' that bring the economic system initially out of equilibrium after which a new equilibrium is found (see Section 2.2.2 for more explanation on the mechanism of a macro-economic model and the effect of 'shocks' to the economy).

dimensions contribute to growth and to decarbonization. When considering the growth side, the focus is placed on the GDP difference and on the overall consumption difference between considering the aforementioned driver into the relative scenario or removing such driver from the same scenario. When considering the decarbonization side the analysis has been directed on measuring the change in demand of energy commodities in the economy and to check to which extent the considered driver would induce change in the energy mix.

Societal Driver

The change in societal behaviour is considered in particular with the Societal Commitment scenario where a gradual shift in consumption from the purchase of manufactured goods to the purchase of services is modelled. This would not only mean that future consumption will focus on services *per se*, but that services will also be used to refurbish existing products to ensure them a longer lifespan. In general, the production of services is obtained with a lower amount of intermediate products. So, an increase in demand for services is expected to entail the formation of a smaller multiplier for the economy, as the effects of a purchase of services ripple to other sectors with lower intensity. This transition in consumption habits is not expected to be able to foster economic growth, as the increase in demand for services is offset by the decrease in demand for industrial production. Services might end up producing smaller ripple effects through the other sectors in the economy, and this might lead to the definition of a smaller GDP compared to a scenario where a circular economy paradigm is not adopted, even if the final consumption level grows. On the other hand, the decrease in intermediate expenditure, normally featuring transport and other energy services results in a decrease in overall consumption of energy. Both models agree with such analysis with REMES-EU showing a more radical reduction of energy consumption compared to EXIOMOD. In conclusion, the societal driver, considered as a shift of consumption from goods to services, tends to reduce both GDP and consumption of energy services, whether they are from fossil sources or from renewable ones.

Technological Driver

The change in technology is modelled using different shocks. The first shock is a change in the *energy mix featured in the different sectors* based on the information provided by technology-detailed energy system models and the second shock is an *improvement in energy efficiency* over time. The inclusion of external development of the energy mix is considered under every openENTRANCE scenario, while the improvement of the energy efficiency (over the baseline efficiency improvement) is most strong under the Techno-Friendly and Directed Transition scenario. For this reason, we only consider the effect of energy efficiency on the economic growth and on the decarbonization potential.

When considering energy efficiency improvement, both models show clear positive effects on economic growth and on final consumption. This happens because of the lower need for energy reduces the general production costs. The decrease in costs leads to lower prices, which boosts the demand level and induces a large increase in production. The two models slightly differ in the extent of the possible rebound effects that the economic growth has on the demand for energy commodities. In REMES-EU, the increase in production leads to rebound effects for energy commodities which offsets the initial decrease in demand for fossil fuels, while it leads to a large increase in demand for clean energy. In fact, according to REMES-EU, there is almost no contribution to decarbonisation from this factor alone, i.e. the amount of fossil fuels purchased with and without the contribution of the extra energy efficiency remains the same, but it allows decoupling the decarbonisation from the growth. On the other hand, EXIOMOD does not display rebound effects on the consumption of energy commodities, but agrees on the fact that the overall economic growth will improve, therefore displaying the potential that technology has on decoupling economy and climate issues.

Political Driver

The policy driver is modelled via the increase of taxes with 5 percentage point of the price for the purchase of fossil fuels, coupled with subsidies decreasing the price of electricity from clean and renewable sources with 5 percentage point. The combination of these measures leads to an effective push for decarbonization, effectively reducing the amount of utilized fossil fuels and greatly fostering the development of renewable energy production, while at the same time producing almost no effect on the GDP.

The results of all the considered tests are displayed in Table 3-6.

Table 3-6: Percentage change provided to a selection of economic KPIs by the three main drivers (society, technology and policy) with respect to the reference scenario in 2050.

	EXIOMOD			REMES-EU		
Indicator	Society	Technology	Policy	Society	Technology	Policy
GDP	0,1%	1,2%	0,0%	-2,7%	2,2%	0,1%
Electricity Demand	-2,9%	-5,8%	4,1%	-8,7%	2,0%	13,0%
Oil Demand	-0,7%	-1,7%	-4,0%	-3,8%	2,1%	-0,6%
Gas Demand	-5,9%	-1,9%	0,2%	-6,0%	-2,2%	-2,4%
Biofuels Demand	-18,8%	-13,3%	0,1%	-12,6%	0,9%	-0,5%
Fuels Demand	0,0%	-5,1%	-4,5%	-2,2%	-0,8%	-4,5%
Diesel Demand	1,9%	-3,3%	-3,3%	-2,9%	-1,0%	-4,8%
Gas Demand	3,7%	1,3%	-2,1%	-2,9%	-1,0%	-4,8%

4 Discussion and conclusions

In this study, the macro-economic and environmental impacts of four decarbonization scenarios and one reference scenario are analysed and compared across two macro-economic models, EXIOMOD and REMES-EU.

Four decarbonization storylines are defined in Deliverable 7.1 of H2020 project openEntrance (Auer et al., 2019) and the macro-economic impacts assessed in this document. Each of the storylines aim at reaching a sustainable future through limiting global warming below 2°C (gradual development) or 1.5°C (Directed Transition (DT), Societal Commitment (SC) and Techno Friendly (TF)) is implemented. The underlying behavioural changes and policy measures are different for each storyline. For storyline DT, the main drivers are technological novelty and policy interventions, for TF, it is the combination of technological novelty with smart and pro-active society. Under SC, the smart and pro-active society together with policy interventions should enable the countries in the EU to contribute to reaching the decarbonized future.

The qualitative storylines become scenarios once the stories are translated into quantified input for the models. The four scenarios were initially implemented in a techno-economic bottom-up energy system model: GENeSYS-MOD. The results of this model served as input for the two macro-economic models. This along with additional scenario assumptions that have only been implemented in the two-macro-economic models and are in line with the qualitative descriptions of the storylines. Examples of additional scenario assumptions are energy efficiency and carbon efficiency measures, circular economy (e.g. servitization), a cap on carbon, and taxes and subsidies on the use of specific energy types. The intensity of each measure is increased or decreased with respect to each scenario.

The environmental and macro-economic results of the four openENTRANCE scenarios are compared with a fifth scenario, the reference scenario. The reference scenario presents the business-as-usual situation, based on the EU Reference Scenario (Capros et al., 2016), where only minimal carbon reduction measures are implemented. Besides a comparison between the decarbonization scenarios and the reference scenarios, the results are also compared across the two models.

In general, the two models produce fairly similar results. To ensure that the models are as comparable as possible, at the start of the analysis, exogenous model assumptions have been compared and set equal as much as possible (e.g. the elasticities). Scenario assumptions are also thoroughly discussed and implemented as similarly as possible. However, the models construction are different by design and have slightly different underlying databases (see Section 2.2.3). Also, due to the differences in design, not all scenarios could be implemented similarly. The differences in the two models become most apparent when comparing the *price effects* occurring under the different scenarios. EXIOMOD shows *increasing prices* of fossil fuels, which are driven by the existence and increase of the carbon cap. These high fossil fuel prices in turn result in decreasing demand for fossil fuels. In REMES-EU, on the other hand, the CO2 allowances are supposed to be purchased alongside fossil fuels in proportion to the amount of emission that a particular fuel produces in a given sector.

The increase in CO2 price due to the lower carbon cap over time, lead to a decrease in demand of fossil fuels which, in turn, lead to a *decrease in price* of the aforementioned fuels.

The models are concordant on the majority of the results. They show that the effect of the decarbonization scenarios on GDP is limited. GDP deviates in an openENTRANCE scenario at most with 1% from the reference scenario in 2050. Instead, it is the industrial composition of the economy that is changing. As expected, there is a shift from fossil fuel producing industries towards industries that produce energy based on renewable sources, like hydrogen and electricity. Another sector that increases relatively more under the decarbonization scenarios is the service sector. This result derives from the shift towards a circular economy and away from the old business model of owning a product towards product leasing from the service sector. At the same time, CO2 emissions are decreasing due to the strict cap on carbon. In the earlier years after 2020, the other measures (e.g. energy efficiency, carbon efficiency, energy use in industries from GENeSYS-MOD) are sufficient to stay below the cap for carbon of a specific year. However, the stricter the cap results in a higher need for the financial stimulant to avoid using fossil-based energy sources, i.e. a positive carbon price. This price increases exponentially towards 2050, when emissions have to be reduced with 92% compared to the levels of 1990.

While we believe that the CGE models used in this paper are suitable to study the economic and environmental impact of climate scenarios, several extensions may provide additional useful insight: e.g. (1) an improvement in the labour modules of the models, (2) taking distributional effects into account and (3) taking more climate effects into account than only the effect of temperature increase on labour productivity.

Regarding the labour market modules, both models use a fairly simple labour market assumption with fixed total supply of labour per country, following exogenous growth trajectories towards 2050. Employment in man years can easily (linearly) be added to the analysis. This deliverable made the decision not to investigate employment, because the figures would look quite similar compared to the figures of production. Another reason not to look at employment is that literature shows that decarbonization policies barely affect total employment in a nation (Bulavskaya and Reynès, 2018). More importantly, the policies cause a shift in skills needed and the larger effects take place on the sub-national level (Chateau et al., 2018). Any possible extension to account for these effects is to link the CGE models used here with models with focus on the behavioural side such as system dynamics, agent based or microsimulations.

5 References

Auer. H., Crespo del Granado, P., Backe, S., Pisciella, P., Hainsch K. (2019). Storylines for Low Carbon Futures of the European Energy System, Deliverable 7.1. OpenENTRANCE.

Bulavskaya, T., & Reynès, F. (2018). Job creation and economic impact of renewable energy in the Netherlands. Renewable Energy, 119, 528-538.

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., ... & Kesting, M. (2016). EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050.

Chateau, J., Bibas, R., & Lanzi, E. (2018). Impacts of green growth policies on labour markets and wage income distribution: a general equilibrium application to climate and energy policies.

Climate-data, Average temperatures for countries in europe, annually (2022). URL https://en.climate-data.org/europe/

Decker M., and Vasakova, L., (2011). "Energy Roadmap 2050. Impact assessment and scenario analysis," European Commission, Energy, unit A1 Energy policy and analysis.

Hof, A. F., Den Elzen, M. G., Van Vuuren, D. P., Mendoza Beltran, A., & Slingerland, S. (2011). Climate policy after Kyoto. Analytical insights into key issues in the climate negotiations.

IPCC (2021). Climate Change 2021, The Physical Science Basis, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

James, B. D., DeSantis, D. A., & Saur, G. (2016). Hydrogen production pathways cost analysis (2013–2016) (No. DOE-StrategicAnalysis-6231-1). Strategic Analysis Inc., Arlington, VA (United States).

Kelemen, A., Munch, W., Poelman, H., Gakova, Z., Dijkstra, L., & Torighelli, B. (2009). Regions 2020: The climate change challenge for European regions. European Commission Rep, 27.

Koesler, S., & Schymura, M. (2015). Substitution elasticities in a constant elasticity of substitution framework–empirical estimates using nonlinear least squares. Economic Systems Research, 27(1), 101-121.

Kowalkowski, C., Gebauer, H., Kamp, B., & Parry, G. (2017). Servitization and deservitization: Overview, concepts, and definitions. Industrial Marketing Management, 60, 4–10.

McFarland, J. R., & Herzog, H. J. (2006). Incorporating carbon capture and storage technologies in integrated assessment models. Energy Economics, 28(5-6), 632-652.

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

Watkiss, P., Troeltzsch, J., McGlade, K., & Watkiss, M. (2019). The Economic Cost of Climate Change in Europe: Synthesis Report on COACCH Interim Results. Policy brief by the COACCH project.

Yildirim, K., Koyuncu, C., & Koyuncu, J. (2009). Does temperature affect labor productivity: Cross-country evidence. Applied Econometrics and International Development, 9(1), 29-39.

Appendix

Appendix A: description of REMES-EU

The REMES-EU model represents a multi-regional, multi-sectoral dynamic Computable General Equilibrium model. It has been designed primarily to analyze the impacts of different climate policy measures and the interactions between the economies of the European Countries. The incorporation of fuel substitution allows to handle regional issues such as decentralized energy production or transmission needs or to investigate the interaction between the energy sector and the broader economy. The model is flexible in term of its input structure and can accommodate for different geographical and sectorial scopes and it allows for a flexible modeling of new sectors. It considers the effects of different CO2 cap constraints with corresponding CO2 prices. REMES-EU is modelled as Mixed Complementarity Problem, a mathematical structure that allows to define complementary conditions linking mathematical expressions in form of inequalities to non-negative decision variables to ensure that either the inequality is satisfied as equality or the connected variable is zero. Many economic problems can be expressed as complementarity problems. In REMES-EU the complementarity structure is defined to enforce three conditions:

- Zero profit – implies that no production activity makes a positive profit.
- Market clearance – requires that supply is equal or larger than demand for each commodity
- Income balance – requires that all the expenditure of the consumers equal the income

The first condition is to be understood as no activity obtaining extra-profit other than the repayment of the employed capital. This condition is linked to the property of irreversibility, i.e. all the activities are operated at non-negative levels. The second condition is associated to the existence of a non-negative price for the considered commodity. REMES-EU mathematical formulation corresponds to an Arrow-Debreu macroeconomic model implemented using the *Mathematical Programming System for General Equilibrium Analysis* (MPSGE), which is an extension to the GAMS language taking information about the diverse entities of an equilibrium model in templates, which are later “translated” into GAMS code. Regular GAMS code and the MPSGE additions are then merged and compiled by GAMS into solver-readable data to be processed.

The monetary flows featured in the model are represented as in the following diagram:

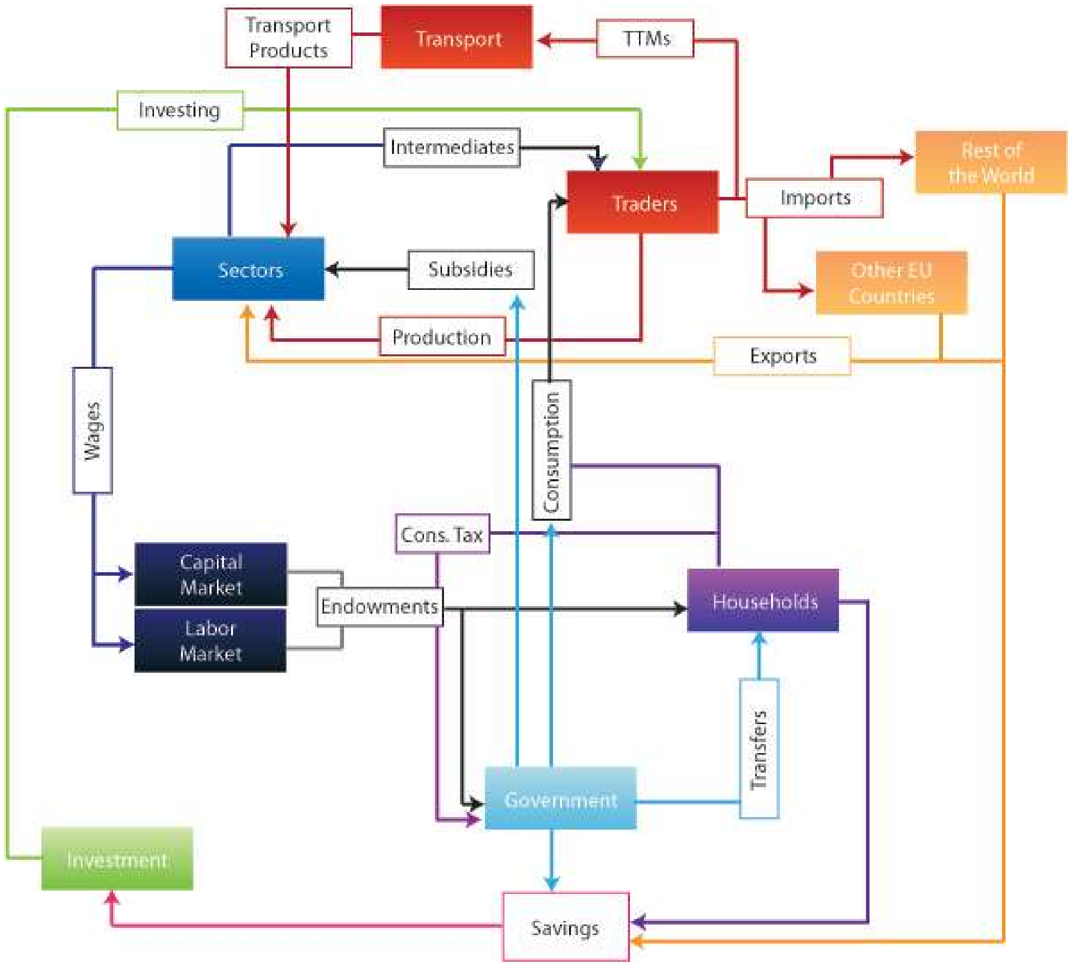


Figure A - 1: Monetary flows in REMES-EU.

In the diagram, traders buy from internal production, imports and transport and trade margins and sell to everyone else (consumers, government, investors and industries). Households buy from traders, send savings to investments according to a pre-specified propensity for savings and pay taxes. On the other hand, they receive money from transfers and endowments from the capital and labour market. Government buys goods and services from traders and sends transfers to households, receiving money flows from taxes. Investors buy from traders and receive savings from Government and Consumers. Consumers, government and investors behaviors are modelled according to a Cobb-Douglas utility function. Industry buys materials and energy commodities from traders, repays labour, capital and taxes, while receiving money from traders and governmental subsidies. Finally, the rest of the world buys from industries (exports) and sell to traders (imports). Capital and labour are assumed as mobile across both sectors and regions. The production of goods is represented through a three nests constant-elasticity-of-substitution (CES) function, assuming a typical KLEM structure. The model particularly emphasizes the role of natural resources such as oil, gas and coal as well as productivity from renewable sources in energy production.

Each sector is identified by a "PROD" MPSGE block in which each input and output is assigned a price, a representative quantity and the current level of taxes applied to each input and to the output. These blocks describe the structure of the (nested) production function. Not only sectors are modelled using these structures, but also consumers preferences by means of utility functions. Consumers and other entities equipped with a budget and a utility function is also equipped with endowments and a budget constraint. These are modelled using a "DEMAND" block. In addition, custom variables can be declared in "CONSTRAINT" blocks to express, for example, dynamically determined taxes or scaling indices. The MPSGE code is structured as follows.

A.1 Households

There is one household per country, representing the aggregated consumption. Households are characterized by a utility function and a set of endowments providing the value for the budget PROD and a DEMAND function.

The utility function of a household can be described using the following structure where we distinguish between non-energy commodities and energy commodities. Energy commodities producing emissions need to be purchased alongside a given amount of allowances, proportionally to the emissions produced by the given fuel in the given sector. The emissions are defined by fuel and sector specific emission coefficients that are multiplied to the amount of each fuel purchased. The fossil fuel (through its emission coefficient) and the related CO2 allowances are linked in Leontief subnests (represented by rectangle-shaped nests). All the inputs are aggregated using a Cobb-Douglas utility function, i.e. using elasticity $\sigma = 1$.

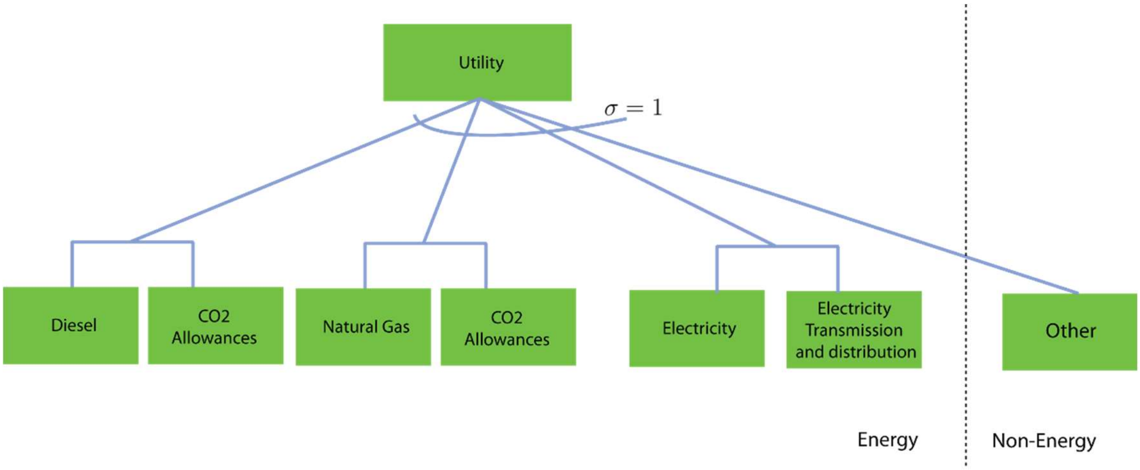


Figure A - 2: Nesting structure of households in REMES-EU.

The purchases of the households are based on a budget depending on their endowments in terms of capital, labour, natural resources and transfers from government and from other countries. The inputs are the worth of the goods purchased and the mark-up on these goods from transport and trade margins (TTMs), both equally adjusted for consumption tax rates. Using these means, households "consume" just enough to spend a budget, which match what they earn by employing their resources. There is a constant TTM rate related to the purchase of goods while the elasticity to combine the goods has been set to one. Taxes on the inputs are assigned to the national government, if it is active, otherwise these go to the local government. The utility function is defined as a Cobb-Douglas with a Leontief subnest to force the complimentary purchase of allowances alongside fossil fuels. Moreover, for energy commodities, a learning curve is used in the energy nest for each considered sector. This curve is used to decrease the amount of energy needed to produce a given output in the production function. Consumption for Investments and Public expenditure follow a similar logic but the earnings come also from taxes for the government and from savings for investments.

A.2 Producers

Producers in the model consume intermediate goods available in the local market (marked up for taxes and the corresponding TTMs), employment of labour and capital, and natural resources. As output, they produce domestic goods. The nests of the production function follow a classic KLEM structure with elasticities σ_{KLEM}, σ_{KLE} and σ_{KL} to describe the substitutability potential betweeen the KLEM, KLE and KL aggregates, while σ_E denotes the elasticity of substitution between the energy commodities. As for the previous case, Leontief subnests are depicted using a rectangle-shaped structure. Capital is aggregated with labour, then the result is aggregated with energy, and finally to materials. Taxes on input goods, as well as taxes/subsidies on output goods are assigned to the governments. Similar to the household utility function, in the energy nest, fossil fuels are aggregated with allowances using a Leontief nest and using a learning curve to describe the improvement in energy efficiency over time.

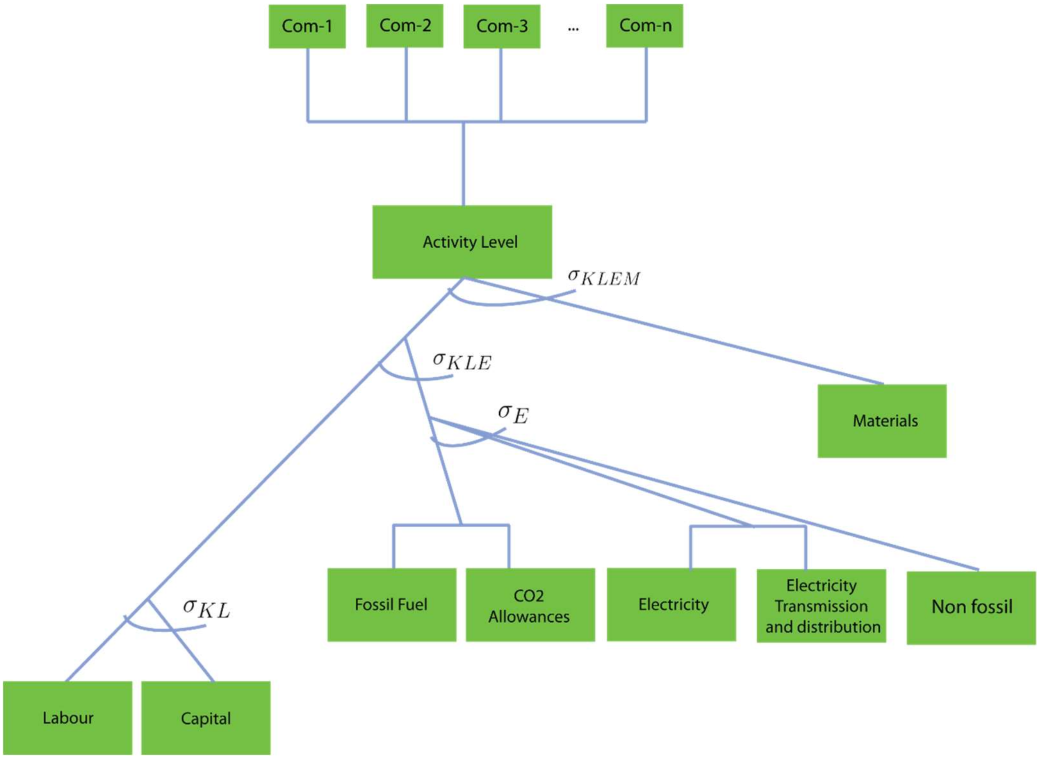


Figure A - 3: Nesting structure of industries in REMES-EU.

The production blocks slightly change for natural resources. Namely, at the top of the nesting structure, there is a further aggregation with the input of the natural resource to be extracted. This is useful to simulate a cap on the availability of the natural resource, for example as a consequence of a law limiting the extractions or the utilization of the resource. Here σ_{KLEMR} denotes the elasticity of substitution with the sector-specific natural resource and the remaining aggregate for production

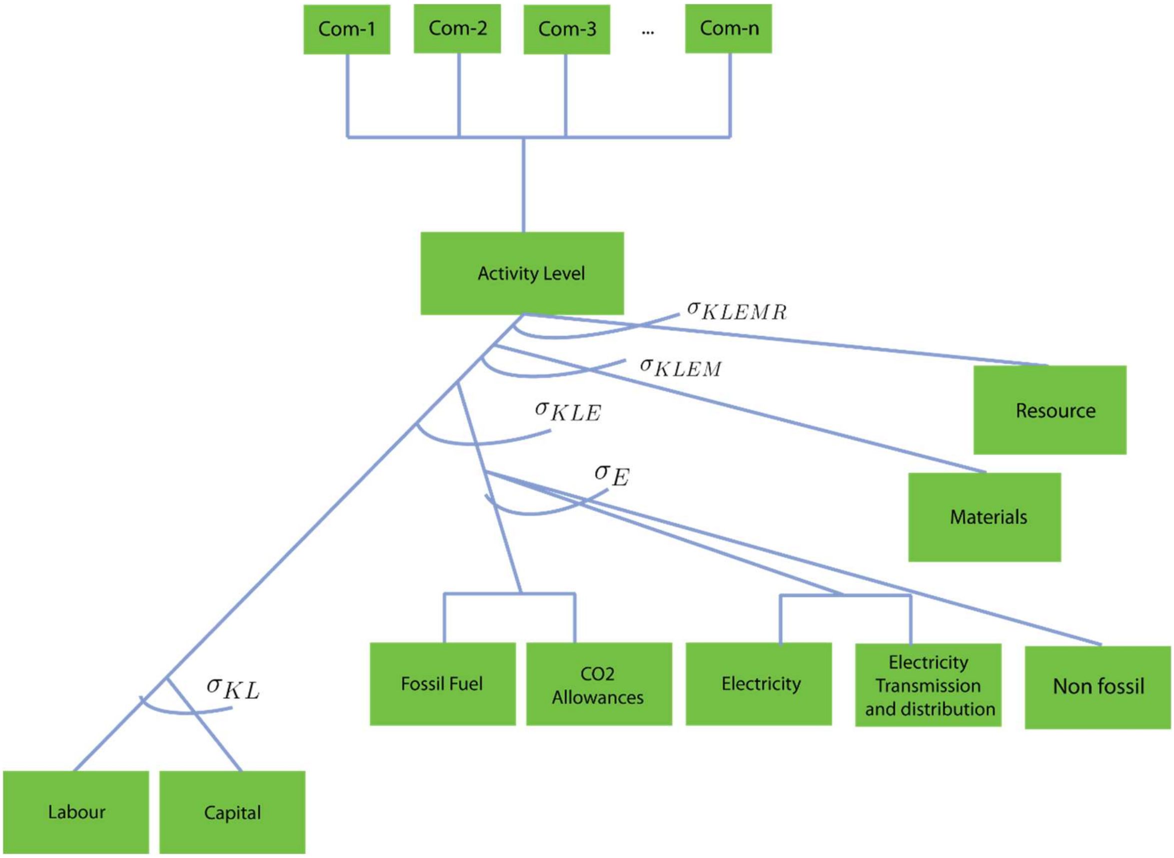


Figure A - 4: Nesting structure of industries in REMES-EU, including resource and material use.

A.3 Exports

The domestic production obtained as output of the production sectors is fed into another function splitting this production into the different geographical markets it is targeting. Namely, a function for the definition of the exports accepts as input the production of a given commodity from different sectors according to a CES function and produces as output the amount of the aforementioned commodity allocated into the domestic market, to each of the explicitly modeled EU countries and to the rest of the World, as shown in the following diagram, where σ_{in} denotes the elasticity of substitution between the same commodity produced by different sectors while t_{out} denotes the elasticity of transformation between product supply for the domestic market, product supply for each of the European Countries engaging in trading with the considered Country and product supply for the rest of the World.

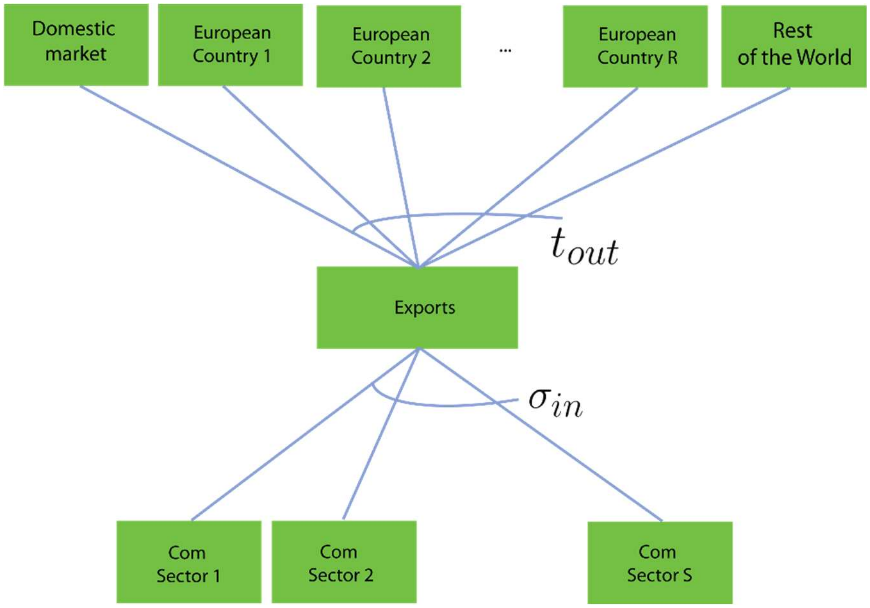


Figure A - 5: Nesting structure of imports and exports in REMES-EU.

The share of the commodity (or service) produced for the domestic market will enter the "Goods" function described in the next block, which together with the share of the same commodity imported from other European countries or from the Rest of the World.

A.4 Goods

This block, for each country and commodity, aggregates imports and domestic production into a representative good that is consumed in the considered country. This is done in accordance to the so-called Armington assumption. For goods produced locally, or in other modelled countries, the block aggregates the value of the trade margin paid to the output price of the Armington good. The block is as follows

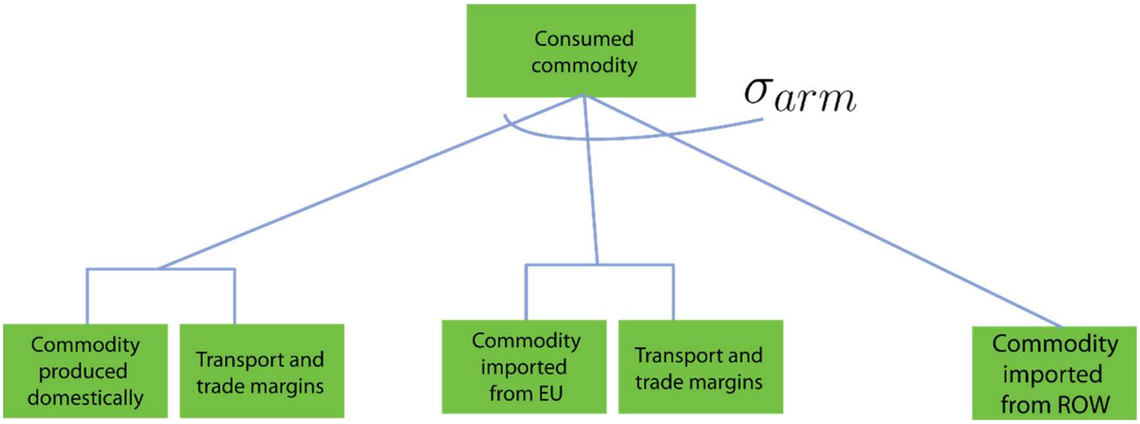


Figure A - 6: Nesting structure of goods in REMES-EU.

Trade margins are defined in a dedicated block, which aggregates a number of services and goods to produce trade and transport services as follows.

Additional constraints in the REMES-EU model are used to scale the endowments in proportion to changes in the economy and to account for changes in employment. A first constraint defines the consumer price index, used to control the transfers from the government to the households, while a second constraint controls the savings level of the government. The third and fourth constraint define the changes in stocks and the savings level of the households. A last constraint defines the unemployment rate, linked to the ratio between the wages and the consumption price index. The wage curve is modelled after the Blanchflower assumption, using an elasticity of 0,1 between wage and unemployment rate.

Appendix B: description of EXIOMOD

This section gives a short description of the model used for this analysis. A more elaborate description is given by (Bulavskaya, 2016).

EXIOMOD is an economic model able to measure the environmental and economic impacts of policies. As a multisector model, it accounts for the economic dependency between sectors. It is also a global and multi-country model with consistent bilateral trade flows between countries at the detailed commodity level. Based on national account data, it can provide compressive scenarios regarding the evolution of key economic variables such as GDP, value-added, turn-over, (intermediary and final) consumption, investment, employment, trade (exports and imports), public spending or taxes. Thanks to its environmental extensions, it makes the link between the economic activities of various agents (sectors, consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases).

Compared to other existing multi-country economic models such as GTAP (Center for Global Trade Analysis - GTAP, 2014), ENV-Linkages (Chateau, 2014), GEM-E3 (Capros P. V., 2013a), E3ME (Cambridge Econometrics, 2014), GINFORS (Lutz, 2010) or NEMESIS (ERASME, n.d.), EXIOMOD 2.0 has several important features that allow customization of the model setup for each study:

- Based on a flexible modular structure, EXIOMOD can run (and compare) several standard economic modelling approaches. Where Input-Output (IO) analysis concentrates on the interdependence between economic sectors, general equilibrium analysis takes also into account price effects. Separating IO from general equilibrium effects simplifies the analysis of the results which overcome certain criticisms formulated to Computational General Equilibrium Models (CGEM) (see below).

- EXIOMOD can have the properties of the two main types of CGEM. Walrasian CGEMs (such GTAP, ENV-Linkages or GEM-E3) assume perfect prices flexibility whereas neo-Keynesian CGEMs (such E3ME, GINFORS or NEMESIS) assume market imperfections (e.g. involuntary unemployment) due to slow adjustment of prices and capital, labour and consumption. This difference may lead to major differences in the results.

- EXIOMOD uses the EXIOBASE database that covers a high level of detail on economic sectors (up to 200 products) as well as environmental extensions on emissions, resources, water and land use.

With these features, EXIOMOD is particularly well suited to evaluate the impact of policies related to climate change, energy and resource efficiency at the macroeconomic, sector and household levels:

- Environmental extensions allows for measuring the impact of economic activities on the use of a large variety of resources and other environmental indicators.

- The international trade flows allows for analysing the impact of national consumption pattern on the economy and on the resource use in other countries. This feature is particularly convenient to confront production based and consumption based indicators of resource footprint per country.

- The modular approach allows for separating direct and indirect effects, and in particular rebound effects.

B.1 A modular approach

EXIOMOD's name stands for EXtended Input-Output MODel. "Extended" refers to the fact that EXIOMOD can extend the standard Input-Output (IO) analysis in two main directions: (1) to Computational General Equilibrium Model (CGEM) analysis, and (2) to specific topics such as environmental impacts, energy, resources or transport. EXIOMOD is based on a modular approach specifically designed to conduct both IO analysis and CGEM simulation. With this modular approach and depending on the subject under investigation, the modeller can easily change the regional and sectorial segmentation as well as the level of complexity regarding the specification of the model by switching on or off specific blocks. This allows for customization, resulting in an appropriate model setup for each research question.

The main objective of this modular approach is to overcome several criticisms formulated to standard CGEMs. In particular, an important issue for the analyses of results obtained with a multi-sector and/or multi-region CGEM is the abundance of linkages and effects which are difficult to separate from one to another. This is all the more true since the results heavily depend on many assumptions such as the level of elasticity, closing rule, underlying data for the sector disaggregation. To some extent, CGEMs have become too complex to answer specific questions which are paradoxically embedded in them. Typically, whereas CGEMs use IO database, the complexity of their production and consumption structure makes it difficult to isolate IO from CGE effects.

On the contrary, EXIOMOD can distinguish different key effects embodied in CGEM which can greatly help the interpretation of the results. In particular, it can separate volume and price effects. The volume effects are directly derived from the IO analysis whereas price effects come from the general equilibrium framework. Within volume effects, EXIOMOD can isolate direct and indirect effects through the calculation of different type of multipliers (multipliers of intermediaries, of investments and of consumption).

B.2 Economic and environmental data

The current version of EXIOMOD uses the detailed Multi-regional Environmentally Extended Supply and Use (SU) / Input Output (IO) database EXIOBASE 3.0 (www.exiobase.eu). This database has been developed by harmonizing and increasing the sectorial disaggregation of national SU and IO tables for a large number of countries, estimating emissions and resource extractions by industry, harmonizing trade flows between countries per type of commodities. Moreover, it includes a physical (in addition to the monetary) representation for each material and resource use per sector and country.

The EXIOBASE database has one of the most detailed product and environmental extensions that are currently available from input-output tables. The database covers 49 regions (44 countries and five rest of the world regions), 200 product groups and various environmental indicators. For the project CICERONE, the economic database has been updated and rebalanced with recycling information from material flow analysis and data from Eurostat.

The environmental indicators are available as an extension to the input-output tables and are listed in Table B - 1. Note that the 165 types of crops follow the FAO classification and are much more disaggregated than the crops in the input-output tables. The data for GHG emissions deviated a bit from the data on Eurostat. For CICERONE, the EXIOBASE database has been updated with data from Eurostat.

Table B - 1: Physical extension in EXIOBASE 3.0 underlying to EXIOMOD 2.0.

Indicator	Level of detail	Examples
Emissions in kg	31 GHG and non GHG emissions	• CO_2 • CH_4 • N_2O • NH_3
Resource use in kg	165 types of crops	• Soybeans • Almonds • Cocoa beans
Resource use in kg Water use in Mm3	8 types of non-metallic minerals	• Slate • Gravel and sand • Salt
	9 types of fossil fuels	• Anthracite • Peat • Crude oil
	10 types of metals	• Iron • Copper • Lead

B.3 Conducting IO and CGEM analysis

EXIOMOD can perform a standard IO analysis which is typically useful to answer to the following type of questions. What is the economic impact of developing a particular sector (in terms of employment, value-added, investment, etc.)? Will domestic or foreign producers benefit the most? Which other economic sectors will benefit from it? With the inclusion of environmental extensions, IO tables can also be used to derive and compare various indicators of resource use: e.g. consumption-based versus production-based indicators. An example is the world map in terms of resource footprints shown in Figure B - 1 as published in the CREEA booklet.

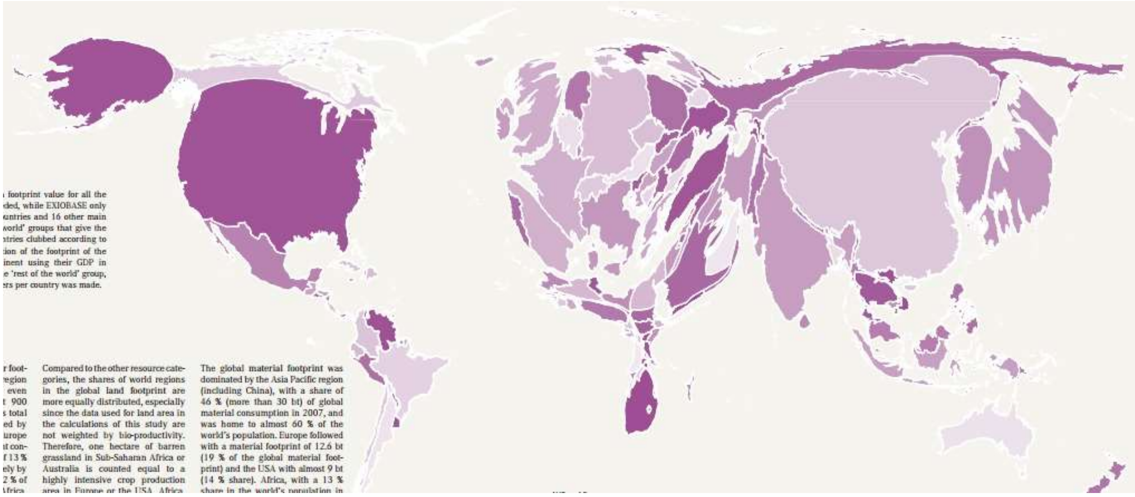


Figure B - 1: Map of resource footprints from EXIOBASE. Source: CREEA booklet.

But IO analysis has the disadvantage to leave price effects aside. The CGE module can be activated to overcome this limit. EXIOMOD is then used as a CGEM. A CGEM takes into account the interaction and feedbacks between supply and demand as schematized in Figure B - 2. Demand (consumption, investment, exports) defines supply (domestic production and imports). Supply defines in return demand through the incomes generated by the production factors (labour, capital, energy, material, land, etc.). To ensure the equilibrium between supply and demand, an assumption regarding the "closure" of the system has to be done. Existing CGEMs generally choose between two main closures. The Walrasian closure assumes that perfect price flexibility ensures the instantaneous equilibrium between supply and demand. On the contrary, the Keynesian closure assumes that demand defines supply whereas price and quantities are rigid and adjust slowly to the optimum. Depending on the application, EXIOMOD can be run with different closures.

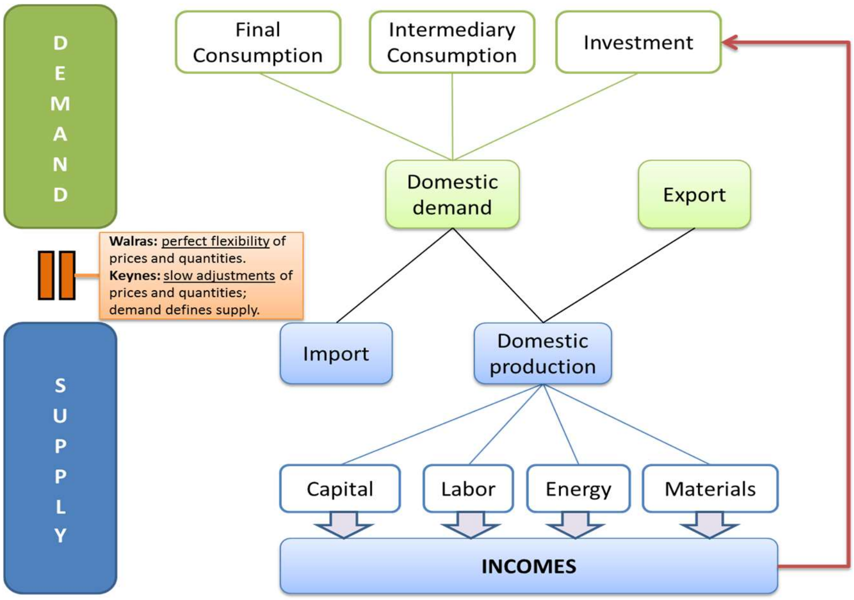


Figure B - 2: General structure of a CGE model.

B.4 Producers

The nesting structure used in the current version of the model is shown in Figure B - 3 but it can be easily adjusted using the modular approach of EXIOMOD. The production technology is modelled as a nested Constant Elasticity of Substitution (CES) functions. The nesting structure allows for introducing different substitution possibilities between different groups of inputs. At the first level, we assume that material inputs for production are perfectly complementary to the aggregate input of capital, labour, energy and that no substitution is possible between these inputs. At the second level, energy can be substituted to the aggregate input capital-labour. At the third level, the elasticity of substitution between labour and capital is equal to one and equals the Cobb-Douglas function.

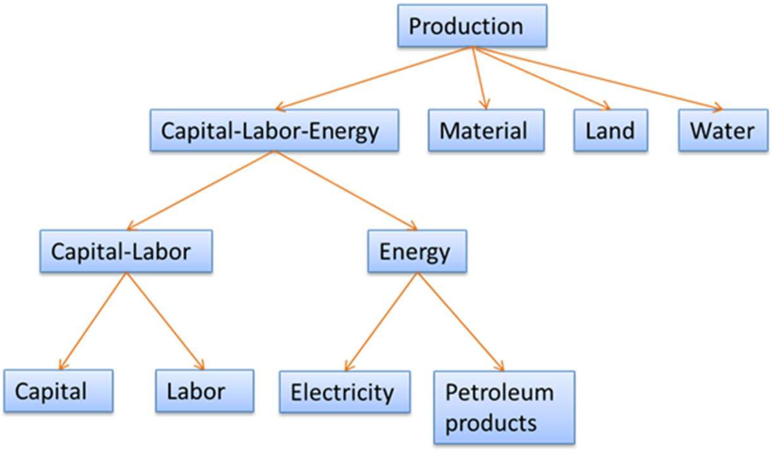


Figure B - 3: Nesting structure of production structure in EXIOMOD 2.0.

B.5 Households

The household's utility is specified as a LES-CES function (Linear Expenditure System - Constant Elasticity of Substitution) allowing to differentiate between necessity and luxury products. This function defines a subsistence level for each good consumed which lead to an elasticity between consumption and revenue lower than one. For instance for food we have a high subsistence level, whereas for other products consumption is more sensitive to the level of income. For instance, the overall subsistence level of consumption corresponds to 33 percent of total consumption, but this level jumps to 80 percent for food products. Above this minimum level of consumption, substitution between goods is possible depending on the price. In the modular approach of EXIOMOD the household's utility function could be switched to the standard CES function in order to simplify the model.

B.6 Trade

The trade structure is schematized in Figure B - 4. At the first level, the user (e.g. final consumer or sectors) can either import a good or buy the good from the domestic market. In a second step, all imported products from the different users are aggregated to calculate the total level of imports. In a third level, imports can be supplied by different countries. We assume a CES function characterized by possibilities of substitutions between regions of origin. We assume that trade in energy, water and construction is much less flexible in terms of changing trade partners compared to trade of other products.

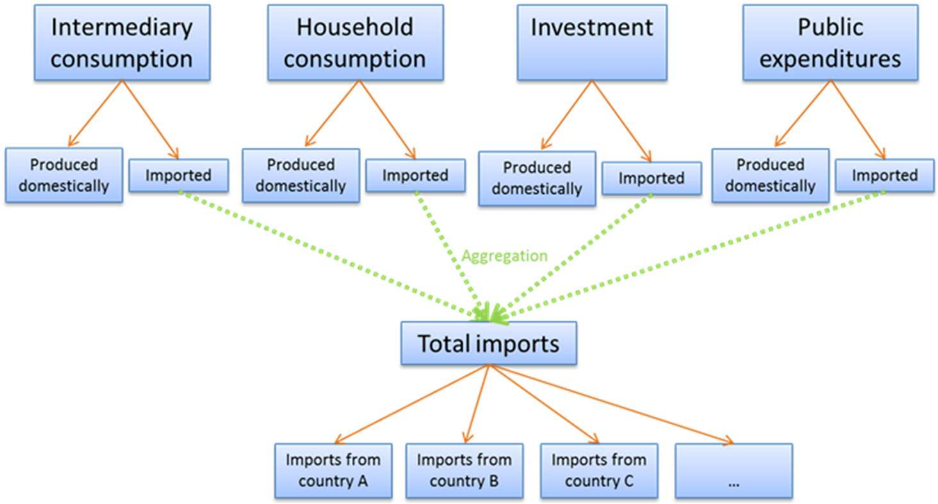


Figure B - 4: Nesting structure of imports and exports in EXIOMOD 2.0.

B.7 Environment

EXIOMOD related the resource use to the economic activity in several ways. CO2 emissions are directly related to the level of consumption of the energy commodities responsible of the emission. Water consumption of economic activities is related to the level of production. For households, it is related to the water consumption (purchased from the water supply sector). Materials (such as metal, non-metallic minerals, etc.) are related to the production of the mining sector responsible of the extraction.

Appendix C: Implementation of scenarios in the models

While the general description of quantification of scenario input to the macro-economic models has been described in Table 2-7, the models have their own specific features (see also Section 2.2.3). Therefore, Table C - 1 and Table C - 2 give model specific explanation of how scenarios are modelled in the respective models EXIOMOD and REMES-EU. For acronyms of industries and products, we refer to Table 2-2 and Table 2-3.

Table C - 1: Description of implementation of quantified model input in EXIOMOD

Reference to quantified input sheet	Description of implementation in the model
GDP and GDP_ROW	GDP growth is implemented via technological progress. In EXIOMOD, the formulas for capital (K) and labour (L) follow Constant Elasticity of Substitution (CES). This function includes a productivity factor. An increase in (labour) productivity implies that with less

	labour input the same production levels can be achieved. Technological progress enables an improvement in (e.g. labour) productivity and thereby increases GDP. Since GDP is an endogenous variable in the model, the exogenous productivity parameters (capital and labour productivity) are calibrated such that in the reference scenario the GDP growth from the EU reference scenario is found. The other scenarios use the calibrated productivity factors for growth in GDP.
POP and POP_ROW	EXIOMOD assumes an exogenous supply of labour. Labour supply by region is exogenously increased using the growth in population. Note that demand for labour by sector and region is endogenously determined. Also, transfers from government to households grow at the rate of population.
CO2_cap	CO2 cap is assumed to decrease by 40% in the reference scenario, by 82% in the Gradual development scenario, by 92% in the Societal Commitment and Directed Transition scenario and Techno-Friendly scenario. Reductions are with respect to the 2007 CO2 cap and implemented for European regions only. The carbon cap is included by introducing an extra CO2-cap module to the model. This CO2-cap module of EXIOMOD is explained in detail in Appendix D.
Materials	A shift of the use of materials to the use of services. This is implemented via the intermediate consumption coefficients (which are exogenously given). These coefficients represent the share of the products required in the production process for each sector-region combination. For servitization, the share of products 'pINDU' and 'pALUM' is reduced according to the scenario and the share of services 'pSERV' is increased with the corresponding aggregated decrease of the two products groups, for each sector-region combination. This factor is particularly emphasised in scenarios where the societal driver is important.
Carbon efficiency	The scenarios assume that carbon efficiency increases over time. That is, for the same amount of economic output in a sector-region combination, corresponding CO2 emissions are expected to decrease. Practically this implies a decreasing trajectory in CO2-coefficients (both combustion and non-combustion).
Energy efficiency	Energy efficiency is implemented via an increase in productivity in energy, the same productivity levels can be achieved using less energy input. The productivity of energy is a parameter in the CES-production function. Where the capital-labour-energy nest is split into a capital-labour nest and an energy-nest. The aggregated energy nest contains all underlying energy products. Energy efficiency is only implemented for all sectors except for energy producing sectors (iH2, iCOIL, iNGAS, iELCO, iELCC, iELCG). For the scenarios characterized by a strong focus on technology, energy efficiency has been increased 20% more than in the other scenarios
Techmix	The shift in electricity from fossil fuel inputs to renewable inputs. This is implemented via the co-production coefficients. For each product it is given which sector-region combination produced the product. Product electricity is produced in EXIOMOD by 10 different electricity producing sectors (electricity produced by coal, gas, hydro, wind, petroleum, biomass, solar, geothermal, nuclear and 'other'). In the base year, most electricity will be produced by grey electricity sectors. Following the scenarios from GENeSYS-MOD, the electricity production shares will gradually move towards renewable electricity sectors.
Energy_use_transport	For each European region, the transport sector changes the shares of the different energy products used in its production. This is implemented via the (exogenously given) intermediate consumption coefficients. Note that the total intermediate input shares for the transport sectors should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs.
Energy_use_industry	For each European region, the manufacturing industry changes the shares of the different energy products used in its production. This is implemented via the (exogenously given)

	intermediate consumption coefficients. Note that the total intermediate input shares for this sector should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs.
Energy_use_hh_and_serv	For each European region, the service sector changes the shares of the different energy products used in its production. This is implemented via the (exogenously given) intermediate consumption coefficients. Note that the total intermediate input shares for the service sectors should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs. In addition, this input from GENeSYS-MOD is also used to adjust the (exogenously given) household energy consumption shares.
Oil extraction level	This is not implemented in EXIOMOD. Only implemented in REMES-EU.
Subsidies and Taxes	A tax of 5% on the consumption of fossil fuels and a subsidy of 5% on the consumption of clean energy commodities is modelled for scenarios with policy as the main focus.

Note that scenarios in EXIOMOD are mostly implemented linearly (except for GDP and population growth where growth years are implemented for each 5 years). Practically, this implies that the data from GENeSYS-MOD are taken for year 2020 and 2050 and interpolated between these two years which removes the nuances in the time trajectories GENeSYS-MOD created. However, the assumption smooths out relatively large fluctuations in the input data resulting in increased stability in the model and ability find an optimal solution. For each scenario, one or more distinctive features have been emphasised to highlight the specific role that one or more of the openENTRANCE drivers (technology, society and policy) play on the considered scenario. To achieve this, we modelled the technology driver as a further improvement of the level of energy efficiency (besides the one considered in the baseline), the societal driver as a shift towards a larger consumption of services and a smaller consumption of manufactured goods and, finally, the policy driver by including a 5% subsidy on the purchase of clean energy and a 5% tax on the purchase of fossil fuels.

Table C - 2: Description of implementation of quantified model input in REMES-EU

Reference to quantified input sheet	Description of implementation in the model
GDP and GDP_ROW	GDP growth is implemented via technological progress. REMES-EU considers productivity of labour extracted using the Kaya chain equality connecting historical emissions to population, GDP per capita, energy intensity and carbon intensity. Moreover, 2% increase in Total Factor Productivity is assumed every 5 years for renewable energy and hydrogen. The growth of capital and labour over time is readjusted with a multiplier that ensures a GDP growth consistent with the one from PRIMES in correspondence of the reference scenario.
POP and POP_ROW	Growth in population is included in the model via growth in labour force. REMES-EU assumes an exogenous supply of labour. Labour supply by region is exogenously increased using the growth in population.
CO2_cap	Implementation of the carbon cap in REMES-EU is explained in detail in Appendix D. CO2 cap in REMES-EU is assumed to decrease by 40% in the reference scenario, by 80% in the Gradual development scenario, by 90% in the Societal Commitment and Directed Transition scenario, by 94% under the Techno-Friendly scenario. Reductions are with respect to base year 2007.

	Carbon cap is modelled by defining the total amount of carbon allowances that can be purchased in a given period. These allowances are considered as a resource similar to capital, labour or a natural resource whose availability is limited and decreases over time. Allowances must be purchased together with fossil fuels in proportion to the amount of emissions that each fuel makes in a given sector.. The fuel and the related allowance are purchased by each sector according to a Leontief production function
Materials	The effects of circular economy are modelled by reducing the percentage of materials in the CES production function of all the production sectors with different amounts depending on the scenario. This factor is particularly emphasized in scenarios where the societal driver is important.
Carbon efficiency	The model considers carbon efficiency applied to the CO2 factors. The efficiency changes linearly from to the base year and reaches the level projected by the World Bank database for 2050.
Energy efficiency	The model considers energy efficiency applied to all the commodities featured in the energy nest of every sector. The efficiency changes linearly from to the base year and reaches the level projected by the World Bank database for 2050. For the scenarios characterized by a strong focus on technology, energy efficiency has been increased 20% more than in the other scenarios
Techmix	The technology mix is treated as input data for the model. The data is collected from the openENTRANCE Scenario Platform. The information is used to modify the Leontief coefficients of the inputs in the energy nest of the production function of the power sector, in the same manner as it is done for considering the technology changes in the other sectors. Note that the total intermediate input shares for this sector should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs.
Energy_use_transport	The energy use in transport is treated as input data for the model. The data is collected from the openENTRANCE Scenario Platform. The information collected is used to modify the Leontief coefficients of the inputs in the energy nest of the production function for transport services. Note that the total intermediate input shares for this sector should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs.
Energy_use_industry	The energy use in industry is treated as input data for the model. The data is collected from the openENTRANCE Scenario Platform. The information collected is used to modify the Leontief coefficients of the inputs in the energy nest of the production function for industry. Note that the total intermediate input shares for this sector should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs.
Energy_use_hh_and_serv	The energy use in households and services is treated as input data for the model. The data is collected from the openENTRANCE Scenario Platform. The information collected is used to modify the Leontief coefficients of the inputs in the energy nest of the utility function for the households and the production function for services. Note that the total intermediate input shares for this sector should still add up to the aggregate in the base case. This scenario does not imply efficiency in production costs.
Oil extraction level	The oil extraction level, as well as the gas and coal extraction level follows a decreasing path over time, both in the reference scenario (10% decrease every 5 years) and in the alternative scenarios (15% decrease every 5 years). This is accomplished by defining a part of the capital for these sectors as the specific resource that is extracted and placing this resource as an input in the top nest of the production function using a low elasticity of substitution with the remaining production aggregate, as shown in Figure A - 7 in the Appendix. This leads to a lower production level (extraction) when the amount of resource is decreasing.
Subsidies and Taxes	A tax of 5% on the consumption of fossil fuels and a subsidy of 5% on the consumption of clean energy commodities is modelled for scenarios with policy as the main focus.

Besides the shocks described in the previous table, REMES-EU considers the behaviour of the Rest of the World by including a rescaling parameter to the output towards the Rest of the World of the CET export function. This happens to simulate uneven distributions of economic wealth in accordance to some of the storylines as well as artificially decrease the export of commodities whose exports have increased without a plausible real justification after the application of the shocks to simulate the openENTRANCE storylines. Such behaviour can happen in REMES-EU due to the way it models the Rest of the World. In fact, REMES-EU does not model consumption of the Rest of the World as it is done for EU countries, but it leaves the import-export pattern to be defined by a terms-of-trade value, which prices imports and exports of all the commodities as if they were a single commodity. Consequently, a decrease in the internal price of a given commodity might result in a quite large increase in demand from the Rest of the World, even if this demand should not increase because of international trends on that given commodity. A typical impact of this modelling approach is that some commodities such as coal might be purchased in a larger volume from the rest of the world after the introduction of CO2 allowances decreases its demand in Europe and leads to a decrease in its price. This will reflect in a gradual, but not particularly strong decrease in coal production in Europe over time.

In addition to the previously considered shocks, climate change effects are for both models included in the scenarios via a reduction in labour productivity due to the increase in temperature (Watkiss et al, 2019). Depending on the scenario, the CO2 emission reduction target is more or less strict, which has an effect on the expected global temperature increase. For each country in the EU and each scenario, the expected effect on labour productivity is calculated and implemented in the models. In particular, the temperature increase in correspondence of the reference scenario is taken from Hof et al., 2011. Average temperatures in Europe is taken from Climate-Data (2022), and distribution of temperature increases over countries is taken from Keleman and Torighelli, 2009.

Appendix D: implementation of carbon cap

C.1 EXIOMOD

In this Appendix it is outlined which <u>extra</u> equations and <u>adjustments</u> to equations are included in the model when we include a carbon cap to macro-economic model EXIOMOD.

<u>Variables</u>

$CO2cap_{reg}$	Exogenous cap on CO2 emissions.
$CO2NC_{reg,ind}$	Non-combustion CO2 emissions by each industry and region

$CO2C_{prd,reg,ind}$	Combustion CO2 emissions by product emitted in industry ind and region reg.
$CO2FD_{prd,reg}$	Combustion CO2 emissions by product and region emitted by final users.
$Y_{reg,ind}$	Output vector on industry level
$ENER_{ener,reg,ind}$	Use of energy types.
$CONS\_H_{prd,reg}$	Household consumption for product prd in region reg.
$CONS\_G_{prd,reg}$	Government consumption for product prd in region reg.
$CO2REV_{reg}$	Revenue from carbon cap.
$PCO2_{reg}$	Price for CO2.
$GRINC\_H_{reg}$	Gross income from households from production factors.
$GRINC\_G_{reg}$	Gross income from governments from production factors.
$PnENER_{reg,ind}$	Aggregate energy price.
$nENER_{reg,ind}$	Use of aggregate energy nest.
$PIU_{prd,reg,ind}$	Aggregate product price for intermediate use.
$PY_{reg,ind}$	Industry output price
$INTERUSE_{prd,reg,ind}$	Use of intermediate inputs on aggregated product level.
$CBUD\_G_{reg}$	Budget available for government consumption.
$CONS\_G_{reg}$	Government consumption on aggregate product level in region reg.
$CBUD\_H_{reg}$	Budget available for household consumption.
$CONS\_H_{reg}$	Household consumption on aggregated product level in region reg.

Parameters

$coefemisnc_{reg,xx}$	Non-combustion CO2 coefficient for industries, households or governments (xx)
$coefemisc_{ener,reg,xx}$	Combustion CO2 coefficient for industries, households or governments (xx)
$tc\_ind_{ener,reg,ind}$	Tax and subsidies on product rates for industry consumption
$eprod_{prd,reg,ind}$	Energy productivity
$alphaE_{ener,reg,ind}$	Relative share parameter for types of energy within the aggregated energy nest.
$elasE_{regg,ind}$	Substitution elasticity between types of energy.
$tc\_h_{prd,reg}$	Tax and subsidies on product rates for household consumption
$theta\_g_{prd,reg}$	Relative share parameter of government consumption on product level in total government demand.
$tc\_g_{prd,reg}$	Tax and subsidies on product rates for government consumption
$elasFU\_G_{reg}$	Substitution elasticity between products for government final use.
$theta\_h_{prd,reg}$	Relative share parameter of household consumption on product level in total government demand.
$elasFU\_H_{reg}$	Substitution elasticity between products for household final use.

A cap is placed on emissions emitted in countries in the EU. This is a country specific cap. This cap should be at equal or larger than all non-combustion ($CO2NC$) and combustion ($CO2C$) industry emissions and emissions from final use ($CO2FD$).

$$CO2cap_{reg} \geq \sum_{ind} CO2NC_{reg,ind} + \sum_{prd,ind} CO2C_{prd,reg,ind} + \sum_{prd} CO2FD_{prd,reg}$$

The price of CO2 ($PCO2_{reg}$) is found via the equation of the cap and is country specific.

Non-combustion emissions of industries are assumed to be linearly related to total economic activity ($Y_{ind,reg}$) of a sector (ind) in a region (reg) via a CO2-coefficient $coefemisnc_{reg,ind}$:

$$CO2NC_{reg,ind} = coefemisnc_{reg,ind} \cdot Y_{reg,ind}$$

Combustion emissions of industries are assumed to be linearly related to non-electricity energy products ($ENER$) used by a sector in a region via CO2-coefficient $coefemisc_{ener,reg,ind}$:

$$CO2C_{ener,reg,ind} = coefemisnc_{ener,reg,ind} \cdot ENER_{ener,reg,ind}.$$

Combustion emissions of households (hh) and governments (gov) are linearly related to non-electricity energy products consumed by households ($CONS\_H$) or governments ($CONS\_G$) in a region via CO2-coefficient $coefemisc_{ener,reg,fd}$:

$$CO2FD_{ener,reg} = coefemisc_{ener,reg,hh} \cdot CONS\_H_{ener,reg} + coefemisc_{ener,reg,gov} \cdot CONS\_G_{ener,reg}.$$

Revenue from CO2 taxation goes to the government. Where CO2 revenue ($CO2REV$) is equal to emissions emitted in a region times the local price of CO2.

$$CO2REV_{reg} = \left(\sum_{ind} CO2NC_{reg,ind} + \sum_{prd,ind} CO2C_{prd,reg,ind} + \sum_{prd} CO2FD_{prd,reg} \right) \cdot PCO2_{reg}$$

Government income ($GRINC\_G$) is equal to income from other sources like capital and labour taxes, but in case of a carbon cap also includes income from CO2 tax revenue.

$$GRINC\_G_{reg} = incomefromothersources_{reg} + CO2REV_{reg}.$$

Industries demand and prices for energy are adjusted such that the CO2 tax influences the energy consumption decision of the industry. The price ($PnENER$) of aggregated energy nest ($nENER$) is a weighted average of the intermediate energy price (PIU) adjusted for industry taxes (tc_ind) of energy use of product $ener$, and the CO2 tax when consuming energy products.

$$PnENER_{reg,ind} \cdot nENER_{reg,ind} = \sum_{ener} PIU_{ener,reg,ind} \cdot ENER_{ener,reg,ind}\left(1 + tc\_ind_{ener,reg,ind} + PCO2_{reg} \cdot coefemisc_{ener,reg,ind}\right).$$

Demand of individual energy products in the energy nest are also responding to the additional CO2 price on non-electricity energy products

$$ENER_{reg,ind} = \left(\frac{nENER_{reg,ind}}{eprod}\right) \cdot alphaE_{ener,reg,ind} \cdot \left(\frac{PIU_{ener,reg,ind} \cdot \left(1 + tc\_ind_{ener,reg,ind} + PCO2_{reg} \cdot coefemisc_{ener,reg,ind}\right)}{eprod_{ener,reg,ind} \cdot PnENER_{reg,ind}}\right)^{-elasE_{regg,ind}}.$$

Industrial output price is directly affected by taxation of emissions. Industry price (PY) is found via the zero-profit condition. Revenues earned from product sales less possible production net taxes are equal to the cost of intermediate inputs and factors of production. In case of the carbon cap, there are additional taxes that need to be paid for the emissions.

$$Y_{reg,ind} \cdot PY_{reg,ind} = \sum_{prd}\left(INTERUSE_{prd,reg,ind} \cdot PIU_{prd,reg,ind} \cdot \left(1 + tc\_ind_{prd,reg,ind}\right)\right) + \left(CO2NC_{reg,ind} + \sum_{prd} CO2C_{prd,reg,ind}\right) \cdot PCO2_{reg} + othertaxes_{reg,ind} + production\_factors$$

The budgets of households (*CBUD_H*) and governments (*CBUD_G*) are also affected by the carbon cap. The following equations for not define household and government budget, however define the scaling parameter of the household and government consumption ($SCLFD\_H$ and $SCLFD\_G$). Consumption prices of households and governments are given by PC_H and PC_G. Taxation of consumption is given by t_ch

$$CBUD\_H_{reg} = \sum_{prd}\left(CONS\_H_{reg} \cdot PC\_H_{prd,reg} \cdot \left(1 + tc\_h_{prd,reg} + PCO2_{reg} * coefemisc_{prd,reg,hh}\right)\right)$$

$$CBUD\_G_{reg} = \sum_{prd}\left(CONS\_G_{reg} \cdot PC\_G_{prd,reg} \cdot \left(1 + tc\_g_{prd,reg} + PCO2_{reg} * coefemisc_{prd,reg,gov}\right)\right)$$

<u>Household and government consumption</u> looks as follows under a carbon cap:

$$CONS\_H_{reg} = CBUD\_H_{reg} \cdot theta\_h_{prd,reg} \cdot \left(1 + tc\_h_{prd,reg} + PCO2_{reg} * coefemisc_{prd,reg,hh}\right)^{elasFU\_H_{reg}}$$

$$CONS\_G_{reg} = CBUD\_H_{reg} \cdot theta\_g_{prd,reg} \cdot \left(1 + tc\_g_{prd,reg} + PCO2_{reg} * coefemisc_{prd,reg,gov}\right)^{elasFU\_G_{reg}}$$

C.2. REMES-EU

To describe how CO2 allowances are modeled in REMES-EU let us introduce the following notation:

Cost Shares

$\theta^{OUT}_{r,s,g}$	Benchmark share of output of commodity g produced by sector s in country r
$\theta^{M}_{r,s}$	Benchmark share of materials in the aggregate output of sector s in country r
$\theta^{E}_{r,s}$	Benchmark share of energy in the aggregate output of sector s in country r
$\theta^{K}_{r,s}$	Benchmark share of capital in the value-added aggregate of sector s in country r
$\theta^{L}_{r,s}$	Benchmark share of labour in the value-added aggregate of sector s in country r
$\theta_{r,s,g}$	Benchmark share of commodity g in its aggregate in sector s and country r
$\theta_{r,s,ET}$	Benchmark share of the electricity and generation and transmission in sector s and country r
$\beta_{r,h,g}$	Benchmark share of consumption of commodity g by consumer group h in country r

Price Variables

$pa_{r,g}$	Consumption price of commodity g in region r
$p_{r,s,g}$	Output price of commodity g from sector s in region r
rkc_{r}	Return to capital in region r
pl_{r}	Wage rate in country r
$p^{CO_2}_{r}$	Price of emission permits in region r
$\theta_{r,s,g}$	Benchmark share of commodity g in its aggregate in sector s and country r
$\theta_{r,h,g}$	Benchmark share of consumption of electricity and electricity transport by consumer group h in country r

Activity Variables

$Y_{r,s}$	Activity level of sector s in country r
$U_{r,h}$	Welfare for consumer h in region r

Parameters

$\alpha_{s,g}^{CO_2}$	CO_2 emission coefficient for energy good g in sector s
$\alpha_{h,g}^{CO_2}$	CO_2 emission coefficient for energy good g for consumer h
$tc_{r,g}$	Consumption tax rate for good g in country r
$tp_{r,s}$	Production tax rate for output of sector s in country r
$\gamma_{r,s}^{L}$	Productivity of labour in sector s and country r
$\overline{CO}_{2,r}$	CO_2 cap in country r

Elasticities

$\sigma_{r,s}^{KL}$	CO_2 emission coefficient for energy good g in sector s
$\sigma_{r,s}^{KLE}$	CO_2 emission coefficient for energy good g for consumer h
$\sigma_{r,s}^{KLEM}$	Consumption tax rate for good g in country r
$\sigma_{r,s}^{E}$	Substitution between energy inputs in energy composite in sector s and country r

REMES-EU is modeled after the Mathiesen format for CGE models. This format considers the CGE as a Mixed Complementarity Problem consisting of three conditions. A zero-profit condition defining whether a sector is in activity or not, a market-clearing condition requiring the supply to match the demand for all commodities through the definition of a price, and finally an income balance constraint, requiring all the expenditure by consumers to match their income after taxes are paid and savings are set apart. The zero-profit condition is defined using the unit revenue and the unit cost for each sector. For a typical sector *s* in country *r* the unit profit is defined as

$$\Pi_{r,s} = \sum_{g} \theta_{r,s,g}^{OUT} \left[\frac{p_{r,s,g}}{\overline{p}_{r,s,g}} \left(1 - tp_{r,s}\right) \right] -$$

$$\left\{ \theta_{r,s}^{M} \left[\sum_{g \in M} \theta_{r,s,g} \frac{pa_{r,g}}{\overline{\overline{pa}}_{r,g}} \left(1 + tc_{r,g}\right) \right]^{1-\sigma_{r,s}^{KLEM}} + \left(1 - \theta_{r,s}^{M}\right) \left[\left(1 - \theta_{r,s}^{E}\right) \left(\theta_{r,s}^{K} rkc_{r}^{1-\sigma_{r,s}^{KL}} + \theta_{r,s}^{L} \gamma_{r,s}^{L} pl_{r}^{1-\sigma_{r,s}^{KL}} \right)^{\frac{1-\sigma_{r,s}^{KLE}}{1-\sigma_{r,s}^{KL}}} + \right.\right.$$

$$\theta_{r,s}^{E} \left(\sum_{g \in FE} \theta_{r,s,g} \left(\frac{pa_{r,g}}{\overline{\overline{pa}}_{r,g}} \left(1 + tc_{r,g}\right) + \alpha_{s,g}^{CO_2} p_{r}^{CO_2} \right)^{1-\sigma_{r,s}^{E}} + \sum_{g \in CE/ET} \theta_{r,s,g} \left(\frac{pa_{r,g}}{\overline{\overline{pa}}_{r,g}} \left(1 + tc_{r,g}\right) \right)^{1-\sigma_{r,s}^{E}} + \right.$$

$$\left.\left.\left. \theta_{r,s,ET} \left(\theta_{r,s,ele} \frac{pa_{ele,g}}{\overline{\overline{pa}}_{ele,g}} \left(1 + tc_{r,ele}\right) + \theta_{r,s,etr} \frac{pa_{etr,g}}{\overline{\overline{pa}}_{etr,g}} \left(1 + tc_{r,etr}\right) \right)^{1-\sigma_{r,s}^{E}} \right)^{\frac{1-\sigma_{r,s}^{KLE}}{1-\sigma_{r,s}^{E}}} \right]^{\frac{1-\sigma_{r,s}^{KLEM}}{1-\sigma_{r,s}^{KLE}}} \right\}^{\frac{1}{1-\sigma_{r,s}^{KLEM}}}$$

We can see that the commodities related to fossil energy sources (FE) are aggregated with the purchase of CO_2 allowances at price $p_r^{CO_2}$ according to a proportional factor $\alpha_{s,g}^{CO_2}$ according to a Leontief technology. Such conditions are paired with the activity level of the sector so that when the zero-profit condition is satisfied the sector will operate with a non-negative activity level, i.e.

$$0 \leq \Pi_{r,s} \perp Y_{r,s} \geq 0$$

According to Hotellings' Lemma, differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients. In particular, the demand of CO2 allowances from the different sectors is defined as

$$\sum_s \frac{\partial \Pi_{r,s}}{\partial p_r^{CO_2}} Y_{r,s}$$

Analogously, we can define the demand of allowances by the final demand, using the expenditure function of both final consumers. Namely, the utility function for households is defined as a Cobb-Douglas, which leads to the following expenditure function

$$\mathrm{e}_{r,h} = \prod_{g \in G/E} \left(\frac{pa_{r,g}(1 + tc_{r,g})}{\overline{pa}_{r,g}} \right)^{\beta_{r,h,g}} \prod_{g \in FE} \left(\frac{pa_{r,g}}{\overline{pa}_{r,g}} (1 + tc_{r,g}) + \alpha_{h,g}^{CO_2} p_r^{CO_2} \right)^{\beta_{r,h,g}} \cdot$$

$$\cdot \prod_{g \in CE/ET} \left(\frac{pa_{r,g}}{\overline{pa}_{r,g}} (1 + tc_{r,g}) \right)^{\beta_{r,h,g}} \cdot \left(\theta_{r,h,ele} \frac{pa_{ele,g}}{\overline{pa}_{ele,g}} (1 + tc_{r,ele}) + \theta_{r,h,etr} \frac{pa_{etr,g}}{\overline{pa}_{etr,g}} (1 + tc_{r,etr}) \right)^{\beta_{r,h,ET}}$$

The expenditure function for each consumption source (households, government and investors) is paired with the welfare level of the consumer to satisfy the condition

$$pu_{r,h} \leq \mathrm{e}_{r,h} \perp U_{r,h} \geq 0$$

The market clearing condition for CO_2 emission allowances in Country *r* is defined as

$$\overline{CO}_{2,r} \geq \sum_s \frac{\partial \Pi_{r,s}}{\partial p_r^{CO_2}} Y_{r,s} + \sum_h \frac{\partial \mathrm{e}_{r,h}}{\partial p_r^{CO_2}} U_{r,h}$$

where $e_{r,h}$ denotes the expenditure function of the *h* final consumer (households, government and investors) and $\overline{CO}_{2,r}$ is the CO_2 budget. The market-clearing condition is associated with CO_2 prices according to the complementarity

$$0 \leq p_r^{CO_2} \perp \overline{CO}_{2,r} - \sum_s \frac{\partial \Pi_{r,s}}{\partial p_r^{CO_2}} Y_{r,s} - \sum_h \frac{\partial \mathrm{e}_{r,h}}{\partial p_r^{CO_2}} U_{r,h} \geq 0$$